Evaluation of the Use and Effectiveness
of
Wildlife Crossings

SECOND INTERIM REPORT

Prepared for:
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

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NCHRP Project
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EXECUTIVE SUMMARY

Introduction

Until recently, concerted and purposeful activity towards linking transportation services and ecological services into a context-sensitive planning, construction, and monitoring process has not been attempted. As a result, piecemeal and haphazard mitigation approaches have provided little useful data to highway planners, engineers, or biologists that could be generalized to different situations. With the funding of this project, NCHRP 25-27, Evaluation of the Use and Effectiveness of Wildlife Crossings, that has changed. Our charge has been to provide guidance in the form of clearly written guidelines for the selection, configuration, and location of crossing types, as well suggestions for the monitoring and evaluation of crossing effectiveness, and their maintenance. Providing guidance on the use and effectiveness of wildlife crossings to mitigate habitat fragmentation and reduce the number of wildlife vehicle collisions involves thinking in a large scale, context sensitive framework that is based on sound ecological principles. Landscape permeability is the guiding principle for this work, and the foundation for effective mitigation. Our goal for this research project is to develop sound guidelines based on the premise that understanding and establishing landscape permeability guidelines leads to effective landscape connectivity and the restoration of ecosystem integrity. At the same time, the guidelines must allow for efficient and effective transportation infrastructure mitigation in a cost-effective, economic manner. The guidelines will take the form of a final report and a web-based electronic decision tool. The research we conducted to accomplish our charge included an assessment and ranking of current practice and research crossing priorities, including the use of data and models to evaluate the safety effectiveness of wildlife crossing measures and to identify collision prone locations, and to evaluate how the crossings might be placed. Additionally, we studied if roads affected the quality of habitat in close proximity to the road as part of our assessment of landscape permeability. As a continuation of Phase 1, we conducted two research efforts, a North American Telephone survey on the state of the practice and research of wildlife crossings, and a ranking of the priorities by over 400 members of the transportation and ecology professions in North America. In Phase 2, we conducted five research efforts: 1) a safety research analysis of wildlife vehicle collisions (WVC) that included the development of Safety Performance Functions and an analysis of differences obtained when using WVC data vs. deer carcass data, 2) An accuracy modeling effort that involved the relative importance of spatially accurate data, 3) An analysis that investigated the usefulness of different kinds of clustering techniques to detect hotspots of wildlife kill on roads, 4) a field study of small mammals conducted in Utah and in British Columbia that investigated the putative habitat degradation effects of roads, and 5) an investigation into allometric methods to effectively place wildlife crossings to increase habitat permeability. Both Phase 1 and 2 efforts provide linked and important data that will be used to develop web-based guidelines to inform wildlife crossing decisions.

Clearly, transportation departments need reliable methods to identify crash prone locations, identify potential mitigation measures and their placement, and evaluate the effectiveness of mitigation measures already implemented. The research developed in this NCHRP project addressed all of these needs. When transportation departments seek to identify solutions to wildlife-vehicle colllisions, there are serious methodological problems associated with current wildlife vehicle collision research, so meeting these needs requires the use of state of the art methods (such as predictive negative binomial models and empirical Bayes procedures) to produce a widely accepted and useable tool that could be readily applied by Departments of Transportation. However, the choice of which database to use (i.e., wildlife vehicle collisions or carcass collection of wildlife road kills) to evaluate the WVC problem may lead to the identification of different "hot spot" locations and ultimately different countermeasure improvements. This is because 1) reported WVC data may represent only a small portion of the larger number of WVCs that occur [61,201], and 2) the spatial location accuracy of the data sets can influence the validity of wildlife-vehicle colllision models. The identification of collision-prone locations from model results is one step in the location of appropriate wildlife crossings. In order to better identify potential mitigation measures for wildlife along transportation corridors, it is necessary to not only identify crash-prone locations, but also areas where landscape permeability can be addressed for suites of species. Although crossings may be constructed based in part on the models and provide some measure of connectivity, landscape permeability as experienced by the animal may not be achieved, because of differences in movement ability between species. The allometric relationship between dispersal distances and home range size of mammalian species can be important in deciding on the placement of wildlife crossing structures that will help restore landscape permeability across fragmented habitat networks. The placement of wildlife crossings, in accordance with the movement needs of suites of species, when used with additional information regarding hot spots of animal vehicle crashes as well as dead animal counts on roads, along with appropriate auxiliary mitigation such as exclusion fences and right-of-way escape structures, should significantly improve road safety as well as provide for easier movement of wildlife across the roaded landscape. Even when wildlife crossings are appropriately placed, it is possible that road effects may include habitat loss or degradation at some distance from the road, even though the roaded landscape is permeable. It is necessary that mitigation efforts be evaluated for not only their efficacy in reducing WVCs but also their ability in allowing multiple species to move across the roaded landscape, thus promoting permeability. The seven research projects we conducted in Phases 1 and 2 as part of NCHRP 25-27 address these issues and provide useable data that will inform the decision tool. Below we give the essential findings from each of the research efforts.

The study is divided into two phases (see STRUCTURE OF THIS REPORT). Phase 1 (30 June – 30 November 2004) entailed: 1) an investigation of current relevant research and practices concerning wildlife crossings *(Tasks 1 & 2);* and 2) an identification of significant gaps and priorities in both research and practice *(Task 3)*. Phase 2 entailed 5 distinct research efforts to help bridge the knowledge gaps in research *(Task 7)*; and development of a web-based decision tool *(Task 8)*. This Second Interim Report provides documentation for the research team's activities to date (1 June 2006). First, we provide

brief introductory material to provide context and suggest how the work is integrated. We then include a progress update for Tasks 1-3 from Phase 1. Results from the five Phase 2 research studies conducted as part of _Task 7_ are then presented project by project. Finally we provide an update on progress towards developing the decision tool _(Task 8)_.

Phase 1 Update

2.1 Literature Review

Members of the team continually search the literature pertaining to wildlife and roads and wildlife-vehicle colllisions. The references are entered into the online database of literature for this project. The majority of references are annotated with key words and a description of the research methods and results. As of May 31, 2006, there are >300 references in our database. We will explore the legality of making these articles available on the website for use in the decision tool and other queries. The literature review will be an ongoing part of this project until its completion.

2.2 Wildlife Crossings Telephone Survey

The wildlife crossings research reported here is a summation of the North American telephone survey we conducted to document as many wildlife passages as we could find in the U.S. and Canada. Our telephone survey included participants employed by state/provincial and federal agencies, private organizations and companies, and academic institutions. More than 390 respondents answered questions concerning wildlife crossings, planning for wildlife and ecosystems, wildlife-vehicle colllision information, and past, current, and future research activities related to roads and wildlife. Our survey found over 550 terrestrial and 10,000 aquatic crossings in North America. These passages are found in 43 of the United States and in 10 Canadian provinces and 2 territories. Trends found in the practice of wildlife crossings included an increase in the number of target species in mitigation projects, increasing numbers of endangered species as target species for mitigation, increasing involvement of municipal and state agencies, increasing placement of accompanying structures such as fencing and escape jump-out ramps, and a continent-wide neglect in maintenance of these structures. The trends in the science related to wildlife passages included a greater tendency to monitor new passages for efficacy, a broadening of the number of species studied, an increase in the length of monitoring time, increases in the number of scientific partners conducting wildlife passage research, and increasingly sophisticated research technology. We documented several projects in North America where a series of crossings have been, or will be installed to accommodate a suite of species and their movement needs, thus promoting permeability. A list of recommendations is also presented to assist in the research, design, placement, monitoring, and maintenance of crossings. As an extension of the evaluation of the state of the science of wildlife crossings, a review has begun of studies evaluating the use of wildlife passages. Approximately 25 scientific studies assessing the efficacy of 70 terrestrial wildlife passages across North America found that all passages passed wildlife, and 68 of the passages passed the target wildlife species. We are reviewing the

results of these studies as well as creating a methodology for evaluating the ecological effectiveness of wildlife crossings. A further review of the evaluation of the effectiveness of wildlife crossings will be included in the final report.

2.3 Gaps and Priorities

In the first phase of this research we developed a list of priorities based on the team's knowledge of current research and practices in road safety and ecology. During the second phase of this research, we asked approximately 500 ecologists and engineers and road-related professionals across North America to rank these priorities. Our objective was to determine where additional research, field evaluations, and policy actions were needed in order to help maintain or restore landscape connectivity and permeability for wildlife across transportation corridors, while also minimizing wildlife-vehicle collisions. The list of priorities was initially reviewed and annotated by dozens of practitioners and researchers in North America and then ranked and annotated in surveys by persons attending two workshops. The survey was refined and posted on the internet in April 2006, and potential participants were invited to complete the survey by ranking priorities. They were also asked to notify other qualified transportation and ecology professionals and invite them to take the survey. The final list of ranked priorities was the result of the participation of over 400 professionals from across North America. The top five priorities were ranked as follows:

1) Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process
2) Better understand the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information
3) Combine several animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than relying on just one method
4) Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out
5) Develop alternative cost-effective wildlife crossing designs and the principles they are based on

The priorities were developed and ranked in order to help direct research, policy, and management actions across North America that address the issue of reducing the impacts of the roaded landscape on wildlife and ecosystem processes.

Phase 2 Research Studies

3.1 Safety

The safety research involved analyses of wildlife-vehicle colllision (WVC) and road environment data from State Department of Transportation (DOT) sources. Data were analyzed in two parts. In the first part, safety performance functions (SPFs) were calibrated for four states. For each state, three levels of SPFs were developed with varying data requirements. The first level required only the length and annual average

daily traffic volume (AADT) of a road segment (a section of road, generally between significant intersections and having essentially common geometric characteristics). The second level required segments to be classified as flat, rolling, or mountainous terrain. The third level SPFs included additional roadway variables such as average lane width. SPF functions relate police reported WVCs to traffic volume and road environment data usually available in DOT databases. Three SPF applications most relevant to the development of the desired guidelines are included in the report: 1) Network screening to identify roadway segments that may be good candidates for wildlife-vehicle colllision countermeasures, 2) The evaluation of the effectiveness of implemented countermeasures, and 3) Methodology for estimating the effectiveness of potential countermeasures. In general, the calibrated SPFs make good intuitive sense in that the sign, and to some extent the magnitude, of the estimated coefficients and exponents are in accord with expectations. Surprisingly, the exponent of the AADT term (see below), although reasonably consistent for the 3 levels of models in a state, varied considerably across states and across facility types, reflecting differences in traffic operating conditions. The most significant variable found was annual average daily traffic (AADT). For application in another state, or even for application in the same four states for different years to those in the calibration data, the models should be recalibrated to reflect differences across time and space in factors such as collision reporting practices, weather, driver demographics, and wildlife movements. In essence, a multiplier is estimated to reflect these differences by first using the models to predict the number of collisions for a sample of sites for the new state or time period. The sum of the collisions for those sites is divided by the sum of the model predictions to derive the multiplier. In deciding which of the four models is best to adopt for another state, it is necessary to conduct goodness of fit tests. Choosing the most appropriate model is especially important because the exponents for AADT, by far the most dominant variable, differ so much between states. A discussion of these tests is provided in a recent FHWA report.[177] Additional supporting information is presented in the appendices.

The second part involved an evaluation of the hypothesis that the magnitude and patterns of reported WVC and deer carcass removal data as they typically exist at a DOT were different. These two types of data have been used in the past, but their differences could lead to varying and possibly ineffective/inefficient WVC-related policy and countermeasure decision-making. Reported WVCs (which typically are provided by state highway safety enforcement agencies in crash reports) and deer carcass removal locations (which are provided by highway maintenance crews in their daily activity reports) were acquired from Iowa and plotted within a Geographic Information System (GIS) platform. The spatial patterns of the two types of data were clearly different, and their calculated safety measures (e.g., average frequencies) varied. Negative binomial models or SPFs were also created for both the reported WVC and deer carcass removal data. The models for these two types of data, which theoretically describe the same problem, had different coefficients and/or input variables. The use of the GIS plots, safety measures, or predictive models developed as part of this project could, therefore, lead to different WVC-related polices and countermeasure implementation and evaluation decisions. The choice of the database used to define and evaluate the WVC problem and its potential countermeasures should be considered carefully. Recommendations are provided

regarding how the databases might be used appropriately and how the data should be collected.

3.2 Accuracy Modeling

The accuracy modeling involved an investigation into the relative importance of factors associated with wildlife killed on the road using two different datasets: one based on spatially accurate location data (<3 m error) representing an ideal situation; and a second dataset created from the first, that was characterized by high spatial error (≤0.5 mile or 800 m) and is likely typical of most transportation agency data. The goal of this research was to summarize how well these models identify causes of WVCs. In this report we used ungulate data sets so the primary result of the analysis was that an ungulate vehicle collision model, developed with spatially accurate location data, had high predictive power in identifying factors that contribute to collisions. Perhaps more noteworthy from this exercise was the vast difference in predictive ability between the models developed with spatially accurate data and the less accurate data obtained from referencing WVCs to a mile-marker system. Besides learning about the parameters that contribute to WVCs in our study area, we discovered that spatially accurate data does make a difference in the ability of models to provide not just statistically significant results, but more importantly, biologically meaningful results for transportation and resource managers responsible for reducing WVCs and improving motorist safety. The results have important implications for transportation agencies that may be analyzing data that has been referenced to a mile-marker system, or unknowingly is spatially inaccurate. These findings lend support to the development of a national standard for the recording of wildlife–vehicle collisions, as well as further research into new technologies that will enable transportation agencies to collect data that are more accurate. Some transportation agencies are beginning to use Personal Data Assistants (PDAs) in combination with a GPS for routine highway maintenance activities (e.g., Washington State[168])These two initiatives can help agencies collect more spatially accurate and standardized data that will eventually lead to more informed analyses for transportation decision-making. This project also investigated the types of variables that explain wildlife–vehicle collisions, in particular whether they are associated with landscape and habitat characteristics or physical features of the road itself. In two different types of analyses, we identified that variables related to landscape and habitat were more significant than variables identified to road characteristics. Through this project, we demonstrate how wildlife-vehicle collision data can be used to aid transportation management decision making and mitigation planning for wildlife.

3.3 Hotspot Analysis

The hotspot analysis investigated several wildlife kill hotspot identification clustering techniques within a GIS framework that can be used in a variety of landscapes. These techniques take into account different scales of application and transportation management concerns such as motorist safety and endangered species management. We obtained animal carcass datasets from two locations in North America with different

wildlife communities, landscapes, and transport planning issues. We demonstrate how this information can be used to identify WVC hotspots at different scales of application, from project level to state level analysis. Some clustering techniques that we tested include Ripley's K-statistic of road-kills, nearest-neighbor measurements, and density measures. We provide an overview of software applications that facilitate these types of analyses. The use of GIS-based information linked to hotspot data was also addressed. Using demonstrated methods, results, and applications of results we will suggest guidelines for the use, analysis, and applications of WVC for transportation planning practices.

3.4 Small Mammals and Putative Habitat Degradation Effects

The small mammal research involved an assessment of the potential of roads to affect the demographics and distribution of small mammals by possible habitat degradation. We investigate what influence, if any, highways had on the relative abundance of small mammals and how far any observed effect might extend into adjacent habitat. We conducted field studies both in Utah and in British Columbia. In Utah, we captured 484 individuals of 13 species. Our results showed different trends of species diversity at different distances from the road from one year to the next. During 2004, the diversity of species was highest further from the road in direct contrast to 2005, when diversity was highest closest to the road. Density and abundance data also differed between years and species. When we compared density in three distinct areas, sites with higher habitat quality; i.e., with greater forb and grass presence, had significantly higher small mammal densities. Overall, it appeared that roads per se had little effect on small mammal density. Rather, microhabitat conditions that were most favorable for each individual species appeared to be most responsible for density responses. The results were similar for British Columbia, where we captured 401 individuals of 11 species. Our results show that highway and transmission line right-of-ways (ROWs) appeared to be negative influences on abundance for most species and potentially neutral to positive for others. There were no consistent patterns in species abundance as the distance in a forest increased from the road right-of-way. There was however, a consistent pattern of lower total species diversity in the road right-of-ways. Microhabitats and local conditions that varied among sites and transects and that remain independent of road or ROW, appeared to be stronger than, or at least mask, any effects related to the road or ROW. For the most common and most habitat-generalized species, the deer mouse (*Peromyscus maniculatus*), there were no strong indications of an effect of distance from the highway or transmission line, nor evidence of any effect attributable to the highway that was not evident at the transmission line sites. Impacts due to the highway itself may exist for some species, but large samples and highly consistent habitat conditions would be required to detect them.

3.5 Allometric Placing of Wildlife Crossings

In the research of allometric placement of crossings, we investigated whether differences in vagility; i.e., the natural ability of animal species to move across the landscape, could be used in deciding on the spacing of wildlife crossing structures that

will help restore landscape permeability across fragmented habitat networks. Until now, the placement of crossing structures has not been grounded in theory but has relied on empirical data to underpin crossing placement decisions, in part because the idea of landscape permeability has not been traditionally viewed from an animal perspective. When landscape permeability is viewed from an animal perspective, inherent species-specific movement capabilities provide the basis for developing scaling relationships (i.e., allometry) to inform the placement of crossings. In other words, the animals 'tell' us where to place the crossings. There have been useful developments in allometric scaling laws that have led to important and statistically sound relationships between home range size and dispersal distance for species. The recently described implications of the relationship of Median Dispersal Distance (MedDD) to home range area, and the development of a single metric, termed the Linear Home Range Distance (LHRD) to represent home range size, provide scaling laws that can be related to the concepts of ecological neighborhoods and domains of scale to consider how the movement of species with similar movement capabilities can be enhanced by effective placement of crossing structures in roaded landscapes. In turn, this will reduce fragmentation effects and improve permeability across habitat networks. It is possible to use MedDD ($7 * \sqrt{}$ Home Range) as the upper bound, and a LHRD ($\sqrt{}$ Home Range) as the lower bound to develop alternative domains of scale for groups of animals to guide the placement of wildlife crossings.

The correct spacing of crossings is perhaps most urgent for large terrestrial mammals, that when involved in wildlife-vehicle crashes, tend to result in greater vehicle damage and greater potential for human injury and death than smaller body-sized animals. Large-bodied animals pose a greater safety risk. It appears that to achieve the kind of landscape permeability that will help insure the health of large mammal populations (i.e., deer, moose, elk, and bear) and to minimize wildlife-vehicle crashes, placement of wildlife crossings in areas where populations of these animals exist will entail at least a multi-step decision process. The first involves deciding which allometric scaling domain is appropriate and feasible. Highest permeability will be obtained when crossings of appropriate type and design are placed using the Linear Home Range Distance domains. If crossings were placed according to the Med DD they would be too far apart to create high permeability of the landscape. For example, using LHRD domains, wildlife crossings for white-tailed deer and mule deer would be placed at about 1 mile (1.6 km) apart in areas where these animals cross the road frequently and are often hit by vehicles, and would certainly improve highway safety and help insure ease of movement, improving landscape permeability for these animals. Using the MedDD values of 6.1 to 7.4 miles to space the crossings clearly is inappropriate and will do little to reduce wildlife-vehicle colllisions or facilitate movement. Similar arguments are appropriate for all species in general. However, the use of allometric scaling domains represents only the first step to inform the placement and spacing of wildlife crossings. Additional local information including: 1) location of migration pathways, 2) knowledge of areas of local animal movement across roads, and 3) hot spots of wildlife-vehicle colllision locations as well as dead animal count locations are needed. When these data are used in an integrated and context-sensitive mitigation, these measures should help

insure landscape permeability, providing for easier movement across the roaded landscape, and significantly improve highway safety.

Interpretation of Research Results

The Phase 2 Research Studies (3.1 Safety, 3.2 Accuracy Modeling, 3.3 Hotspot Analysis, 3.4 Small Mammals and Putative Habitat Degradation Effects, 3.5 Allometric Placing of Wildlife Crossings) contain valuable information and suggestions for implementation. In particular, sections 3.1, 3.2, and 3.3 address different ways to achieve similar purposes. For example, section 3.1 (Safety) involved analyses of wildlife-vehicle collisions (WVC) and road environment data from State Department of Transportation (DOT) sources. Section 3.2 (Accuracy Modeling) involved an investigation into the relative importance of factors associated with wildlife killed on the road using two different datasets: one based on spatially accurate location data (<3 m error) representing an ideal situation; and a second dataset created from the first that was characterized by high spatial error (≤0.5 mile or 800 m) and likely typical of most transportation agency data. Section 3.3 (Hotspot Analysis) investigated several wildlife kill hotspot identification clustering techniques within a GIS framework that can be used in a variety of landscapes. The purpose of this section (Interpretation of Research Results) is to guide the reader when considering which analysis to use.

The safety research (section 3.1) is most effectively used when the purpose is to assess if a specific mitigation has been successful in reducing WVCs. Predictive models for animal–vehicle crashes, also called safety performance functions (SPF) are models derived from historical data to relate collision frequency to physical roadway and roadside characteristics. The approach is statistically correct and accounts for "regression to the mean" problems. It makes use of three different levels of road data commonly available. The first level requires data on: 1) road length; and 2) annual average daily traffic volume (ADDT). The second level adds the requirement that road segments to be classified as flat, rolling, or mountainous terrain. The third level incorporates the data used in levels 1 and 2, but includes additional roadway variables such as average lane width. The safety approach has several applications and can be used to:
1) Identify roadway factors associated with a high propensity for animal–vehicle collisions. The approach can be useful in roadway design and planning decisions that have implications for animal–vehicle collisions. The cautions pertain to possible counterintuitive inferences that may result from omitted, incorrectly specified, or correlated factors not included in the analysis; e.g. environmental and topographic variables.
2) Identify roadway segments that may be good candidates for animal–vehicle collision countermeasures.
3) Estimate the effectiveness of potential countermeasures that are considered for candidate segments.
4) Evaluate the effectiveness of implemented countermeasures using state of the art methods for observational before-after studies. The safety approach focuses

explicitly on whether WVCs have been reduced by the mitigation in place. An important caveat is that the safety approach does not address any aspect of wildlife population response. Significantly, the before-after analysis may be judged as successful from a road safety perspective, at the same time that the wildlife population concerned has been significantly reduced.

The accuracy modeling (section 3.2) involved an investigation into the relative importance of factors associated with wildlife killed on the road using spatially accurate and inaccurate datasets. The research, however, used not only road data, but off-road environmental data that had high predictive power in identifying factors that contribute to WVCs. The safety approach recognized that variables other than road related variables might be important (see caution above). Besides learning about the parameters that contributed to WVCs, we discovered that spatially accurate data does make a difference in the ability of models to provide not just statistically significant results, but more importantly, biologically meaningful results for transportation and resource managers responsible for reducing WVCs and improving motorist safety.

The hotspot analysis (section 3.3) investigated WVC hotspot identification techniques, taking into account different scales of application and transportation management concerns. Data on hotspots of WVCs can aid transportation managers to increase motorist safety or habitat connectivity for wildlife by providing safe passage for wildlife across busy roadways. Knowledge of the geographic location and severity of WVCs is a prerequisite for devising mitigation schemes that can be incorporated into future infrastructure projects (bridge reconstruction, highway expansion). As an initial step, we used the Linear Nearest Neighbor Index (a simple plotting technique) to assess whether the location of dead animals found on roads as a result of WVCs were random. The Linear Nearest Neighbor Index used in this analysis is only an indicator of first order spatial randomness, i.e., an indicator to what extent the animal kill locations may be clumped. The expectation is that topography, vegetation characteristics, animal behavior, and roadway characteristics, including traffic volume and speed have something to do with wildlife mortality on roads and that dead animals tend to cluster in hotspots on roads. We present three analytical clustering techniques (Ripley's K-statistic of road-kills, nearest-neighbor measurements, and density measures) to more formally identify WVC hotspot locations if clustering is found. With simple plotting of WVCs, there is a tendency for road-kill points to overlap and visually mask the importance of segments of highway that have a high density of WVCs. Modeling or analytical techniques permit a more detailed assessment of where WVCs occur, their intensity, and the means to begin prioritizing highway segments for potential mitigation applications. The identification and delineation of WVC clusters, which often vary widely in length depending on distribution and intensity of collisions, facilitates between-year or multi-year analyses of the stability or dynamics of WVC hotspot locations. The WVC data that transportation departments currently possess are suitable for meeting the primary objective of identifying hotspot locations at a range of geographic scales, from project-level (<50 km of highway) to larger district-level or state-wide assessments on larger highway network systems. The spatial accuracy of WVCs is not of critical importance for the relatively coarse-scale analysis of where hotspots are located. Any of the analytical clustering techniques can be used, when more detailed information is needed.

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STRUCTURE OF SECOND INTERIM REPORT

Project 25-27 FY04 is partitioned into two phases. Phase 1, the subject of the first Interim Report submitted November 2004, was comprised of six tasks:

Task 1: **Analyze, describe, and critique, pertinent domestic and international research, based on applicability, conclusiveness of findings, and usefulness for the accomplishment of the project objectives**

Task 2: **Conduct a survey of current domestic and international practices in the use of wildlife crossings**

Task 3: **Identify and prioritize gaps and needs in the current body of research and practices, and determine where additional research and field evaluation will be required in order to achieve the project objectives**

Task 4: **Develop a plan for new research and field evaluation to fill the gaps identified in Task 3**

Task 5: **Prepare a draft outline and a recommended format for the proposed guidelines**

Task 6: **Submit an interim report within 6 months to document Tasks 1 through 5 for review by the NCHRP**

The first Interim Report was submitted on 29 November 2004, and reviewed in Washington D.C. on 14 January, 2005. Written comments from panel review members through the National Academy of Sciences and Engineering were received by 4 February 2005. The revised report was resubmitted on 17 February 2004 and accepted. Subsequently, Approval of Phase 2 of the project was given and subsequent work includes the following five tasks and is reported herein:

Task 7: **Conduct the research and field evaluation outlined in the Task 4 plan as approved by the NCHRP**

Task 8: **Based on the results of Tasks 1 through 7, develop draft guidelines, and the prototype electronic decision tool**

Task 9: **Submit a second Interim Report within 6 months of contract completion to document the results of Tasks 7 and 8**

Task 10: **Finalize the guidelines and electronic decision tool**

Task 11: **Submit a final report that documents the entire research effort and includes the Task 10 Guidelines and the Decision Tool as stand-alone products. Provide an executive summary and a PowerPoint Presentation that outlines the background, methodology, and findings of the research**

In this Second Interim Report, we provide four chapters. **Chapter 1** includes an **Introduction** that gives background information that places the work done under this project into a larger context. This section is taken largely from the proposal. We also include a statement of the **Objectives** for the project. Finally, we give the overall **Vision** that has guided the conduct of the Project.

Chapter 2 includes updates on **Tasks 2 and 3 from Phase 1**.

Chapter 3 includes the research conducted as directed by Task 4. It includes 5 sections. The first section, **3.1 Safety Data Analysis** includes two parts: <u>Segment 1:</u> The application of reported WVC data typically available in state DOT databases, and <u>Segment 2:</u> An investigation of how the application of two databases, reported WVCs and carcass removals, can lead to different roadway improvement decisions. The second section, **3.2 Accuracy Assessment**, includes analyses of wildlife-vehicle collision data and explores the limiting effects of road-kill reporting data due to spatial inaccuracy. The third section, **3.3 Hotspot Analyses**, investigates various WVC hotspot identification (clustering) techniques that can be used in a variety of landscapes, taking into account different scales of application, from project level to state level analysis, and transportation management concerns (e.g., motorist safety, endangered species management). The fourth section, **3.4 The Influence of Roads on Small Mammals,** investigates the influence highways may have on the relative abundance of small mammals and how far any observed effect might extend into adjacent habitats. The fifth section, **3.5 The Allometric Scaling of Wildlife Crossings** explores whether the relationship between dispersal distances and home range size of mammalian species can be used to develop scaling relationships to decide on the placement of wildlife crossing structures that will help restore landscape permeability across fragmented habitat networks. Each section of Chapter 3 is organized into five parts: 1) Abstract, 2) Introduction, 3) Research Approach: Methods and Data, 4) Interpretation, Appraisal, and Applications, and 5) Conclusions and Suggested Research.

Chapter 4 includes a description of the web-based decision tool with the URL location and instructions on how to use the tool. The Literature Cited and Appendices keyed to the appropriate chapters and sections are given at the end of the document.

CHAPTER 1: INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

"For a generation, North Americans have been in simultaneous pursuit of twin goals that are inherently in conflict. On the one hand, they seek to harvest the manifold benefits of an expanding road system, including a strong economy, more jobs, and better access to schools, friends, family, recreation, and cheaper land on which to build ever larger homes. On the other, they have growing concerns about threats to the natural environment, including air and water quality, wildlife habitat, loss of species, and expanding urban encroachment on rural landscapes. … . Not surprisingly, these conflicting demands clash wherever transportation decisions are made, whether at the federal, state, or local levels…. . ad hoc environmental analysis has left many gaps in our understanding of effective mitigation for individual road projects and is unlikely to ever lead to effective mitigation of the macro effects of a growing system of roads."

Thomas B. Deen, Executive Director (retired)
Transportation Research Board, National Academy of Sciences
Member, National Academy of Engineering
Forward to *Road Ecology: Science and Solutions*

The inherent wisdom behind these words suggests that transportation services and environmental concerns (i.e., 'ecological services') need to be effectively linked in a context-sensitive planning, construction, and monitoring process. Piecemeal and haphazard mitigation approaches have not provided highway planners and engineers with useful data that can be generalized to different situations. For decades, environmental mitigation was not considered an integral part of road construction. However, following the completion of the interstate highway system, a new post-interstate era began with the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA), which effectively shifted responsibilities and funding from national priorities to local needs and greater state and local government authority, while at the same time placing greater emphasis on environmental mitigation and enhancement.[98] In 1998, the Transportation Equity Act for the 21st Century (TEA 21) retained this basic emphasis. The 2005 SAFETEA-LU Transportation Bill continued this move toward environmental mitigation and gave even greater importance to facilitating both terrestrial and aquatic passage of wildlife, while also instructing that when metropolitan plans and statewide plans for transportation are developed, they must include "a discussion of potential environmental mitigation activities and potential areas to carry out these activities"(Safe, Accountable, Flexible, Efficient Transportation Equity Act: a Legacy for Users, Public Law 109-59, Title VI, Sec.6001 Transportation Planning). In Canada, Transport Canada has published Road Safety Vision 2010, which calls for decreases of 30% in the number of road users killed or seriously injured. Over the last decade, legislation and policy including the *National Parks Act* and the Parks Canada Policy document have placed the highest

priority on the protection of ecological integrity, which would include mitigation for wildlife on upgrades to highways within National Parks. Additionally, the recent *Species at Risk Act* in Canada has made planning and mitigation for wildlife collision accidents even more critical a concern for highway planners and engineers. Given the mandate of these major legislative acts, highway planners and engineers across the North American continent have begun to integrate mitigation as part of their mandate. For example, British Columbia has developed a 10 year Strategic Plan to reduce wildlife collisions by 50%. However, even with these forward looking actions and in spite of a voluminous literature on ecological 'road effects', there remains an obvious lack of synthesis documents to inform and help guide highway planners and engineers with environmental mitigation and enhancement. Linking transportation and ecological services effectively requires a synthetic understanding of the science so that mitigation practices may be data based.

Historically, linking transportation and ecological services may have seemed inherently in conflict but they need not be so. One can envision roads as having a physical as well as a virtual footprint. The physical footprint is easy to see and includes the actual dimensions of the road (length and width), as well as the dimensions of associated structures, e.g., the right-of-way. The virtual footprint is much larger and includes the area where the indirect effects of roads are manifested. The roaded landscape has both direct and indirect effects on wildlife species, community biodiversity, and ecosystem health and integrity. The most prevalent *direct effect* is road-kill. *Indirect effects* include direct habitat loss, reduced habitat quality, barrier effects, and loss of connectivity resulting in restricted or changed animal movement patterns. The virtual footprint, therefore, can be understood only when put into a landscape, context-sensitive perspective. Here the 'Cinderella Principle' needs to be applied; namely establishing mitigation that effectively 'shrinks' the virtual footprint to more closely resemble the physical footprint.[26] For surface transportation, this means that highway planners and engineers need to continue to incorporate mitigation measures that restore ecological integrity and landscape connectivity, while at the same time insuring safe state-of-the-art transportation services in a cost effective manner. This is not an inherently difficult job, but it does require purposeful activity guided by informed, synthetic analyses that reflect true benefits and costs. We define transportation services to mean, among other things, safe, efficient, reliable roads, inexpensive transportation, properly constructed intersections, safe and quiet road surfaces, good visibility, safe bridges, and good signage. By ecosystem services, we mean clean water, clean air, uncontaminated soil, natural landscape processes, recreational opportunities, abundant wildlife, normal noise levels, and a connected landscape that leads to restoration and maintenance of life-sustaining ecological processes.

Currently across North America, a mismatch exists. Ecosystem services have been compromised by road construction. The _virtual_ road footprint is too large. We suggest that the overarching principle that needs to guide future road construction, renovation, and maintenance needs to link both transportation and ecological services. That is accomplished by reestablishing multiple connections across the landscape. The mechanism by which connectivity is established involves moving from roaded landscapes that are nearly impermeable, to landscapes that are semi-permeable and finally, fully permeable; when accomplished, the landscape is connected, and ecological services are

restored. Nearly normal hydrologic flow, facilitated animal movement, reconnection of isolated populations and gene flow are made possible. In other words, the Cinderella Principle of 'shrinking the virtual footprint' has been applied effectively, restoring landscape permeability. Ecological objectives have been met coincident with a continually effective roadway network.

The concept and practical application of permeability might best be understood by an example. Imagine a middle-aged couple who live in a small town or suburb. They work close to their home, and shop in the neighborhood. They have walking access to a grocery store, a church, a pharmacy, a movie theater, a medical clinic; in short, all of the amenities they need for a happy and comfortable life. Then suppose that a major road that runs through the suburb is enhanced and made into a four lane divided interstate highway with its accompanying fences and barriers, to accommodate the increased traffic and to provide the requisite and expected transportation services. Because of the location of the road, it now separates our imaginary couple from their work, and from the amenities that they depended on and could access easily before. The couple, who always walked to access these amenities and resources, is now blocked by the highway. The highway does, however, provide *connectivity* in the form of crosswalks spaced approximately 6 to 8 blocks apart. The couple has a choice. They can either use their car and bear with the heavy traffic, or walk many more blocks to access the crosswalks that would allow them to cross the road. It is unsafe for them to cross the highway in any place other then the crosswalks provided. Their cohesive *neighborhood is still connected, but much less permeable.* This is the critical difference between connectivity and permeability. Regardless of the choice they make, accessing the resources the couple needs for everyday life is now much more difficult and entails much longer distances and a greater time commitment. Although fanciful, this imaginary situation is analogous to what happens to ecosystem resources for wildlife when highways are built across natural landscapes.

Connectivity can be maintained by crossings, but the placement, type, and configuration of the crossing will determine whether permeability is impacted. Think of crossings as a funnel that guides animals under or over roads. Then imagine a context-sensitive road design that incorporates different types and designs of crossings in appropriate locations. The result can be thought of as a 'sieve' that facilitates animal movement, rather than a 'funnel'. Connectivity evolves to permeability. Restoring connectivity is a land-based concept and easy to understand. As can be seen by the example given above, it is not necessarily equivalent with the idea of landscape permeability, which is an animal-centered concept.

The difference between the two concepts involves the idea of scale-sensitive (allometric), animal-based movement. Permeability implies the ability of the animal to move across its home range or territory, (its ecological neighborhood) in a relatively unhindered manner, i.e., movement ease can be indexed by essentially a straight-line distance to resources. To put this into scientific terms, the fractal measure of the pathway is non-tortuous and is of low dimension. Anything that *hinders movement* or *increases distance* moves the landscape in the direction of impermeability. Scale-sensitivity considerations enter the picture because different animals have different movement capabilities and respond to the same landscape in very different ways. A mouse does not

use or move across its home range in the same way a moose does. Hence, an assessment of the local animal community that exists in the landscape that the road crosses is essential and will suggest different crossing types, configurations, and locations in order to achieve permeability in roaded landscapes. Understanding animal behavior is critical in achieving permeability.

Providing guidance on the use and effectiveness of wildlife crossings to mitigate habitat fragmentation and reduce the number of wildlife vehicle collisions involves thinking in a large scale, context sensitive framework that is based on sound ecological principles. Connectivity is intimately linked to permeability. Permeability is the goal of smart roads and intelligent mitigation. Our goal for this research project is to develop effective guidelines based on this premise: understanding and establishing landscape permeability guidelines that lead to _effective_ landscape connectivity and the restoration of ecosystem integrity – while continuing to provide efficient and effective transportation infrastructure in a cost-effective economic manner. Research conducted for this project was undertaken with the goal to evaluate how the selection, configuration, and location of crossing facilities can help restore landscape permeability.

According to NCHRP Synthesis 305,[79] motorist safety and the problems resulting from vehicular collisions with wildlife are important concerns. Wildlife–vehicle collision studies are used as an analytical tool to identify overall trends and problem areas because collisions with larger animals can result in substantial damage and personal injury. However, available datasets often do not include collisions with elk, moose, or caribou and seldom address accidents caused by 'swerve to miss' responses by the driver, phenomena which will certainly increase the valuation of damage caused by wildlife–vehicle accidents. There are serious methodological problems associated with current wildlife–vehicle collision research. The research of relevance to safety concerns addressed in this document use relevant data and models to identify collision prone locations and evaluate the safety effectiveness of wildlife crossing measures.

RESEARCH OBJECTIVES

The objectives of this project are to provide guidance in the form of <u>clearly written guidelines</u> for:

> **THE SELECTION OF CROSSING TYPES**
> **THEIR CONFIGURATION**
> **THEIR APPROPRIATE LOCATION**
> **MONITORING AND EVALUATION OF CROSSING EFFECTIVENESS**
> **MAINTENANCE**

The guidelines will take the form of a final report and a web-based electronic decision tool. Completion of the tasks outlined below will provide the data to develop the final report guidelines.

In this Second Interim Report, we provide an update on Tasks 2 and 3 of Phase 1 and report on the Safety and Ecological Research conducted under Tasks 7 and 8. This report constitutes completion of Task 9.

Vision for the Project

This project is driven by the following vision. Integration of the tasks of the project into the decision tool is paramount. Identification of the gaps and priorities for both research and practice were used to develop a state-of-the-art analysis that influenced our approach to Task 4, the research that we will conduct for this project. Integration of two very different research efforts, _Safety_ and _Ecological_, will take a clear focus and overt action to accomplish. Here is why. The safety analyses and the ecological analyses are using essentially the same basic data, (i.e., carcass and animal collision data). Given the focus of the modeling and analyses, either safety or ecological, different auxiliary data are needed. For example, for the safety modeling and analyses, right-of-way data, commonly referred to as ROW geometrics, are coupled with animal–vehicle collision data to provide the bases for the rigorous Empirical Bayesian approach. The primary objective for this modeling and analyses is safety. For the environmental modeling, mapping, and analyses, off-road variables, coupled with either carcass or wildlife vehicle collision data provide the basis for the rigorous approaches used, although some ROW variables may be included. The primary objective for this modeling and analyses is aimed at landscape permeability and healthy animal populations. In other words, the fundamental data set (carcass data or animal collision data) is used with different variables for very different purposes. Both safety and ecological approaches are necessary to effectively select the type, number, and location of crossing facilities. When integrated, issues of both safety and landscape permeability are satisfied (Figure 1). The goal of this project is to develop and integrate these two fundamentally different research approaches and incorporate them effectively into the final decision tool.
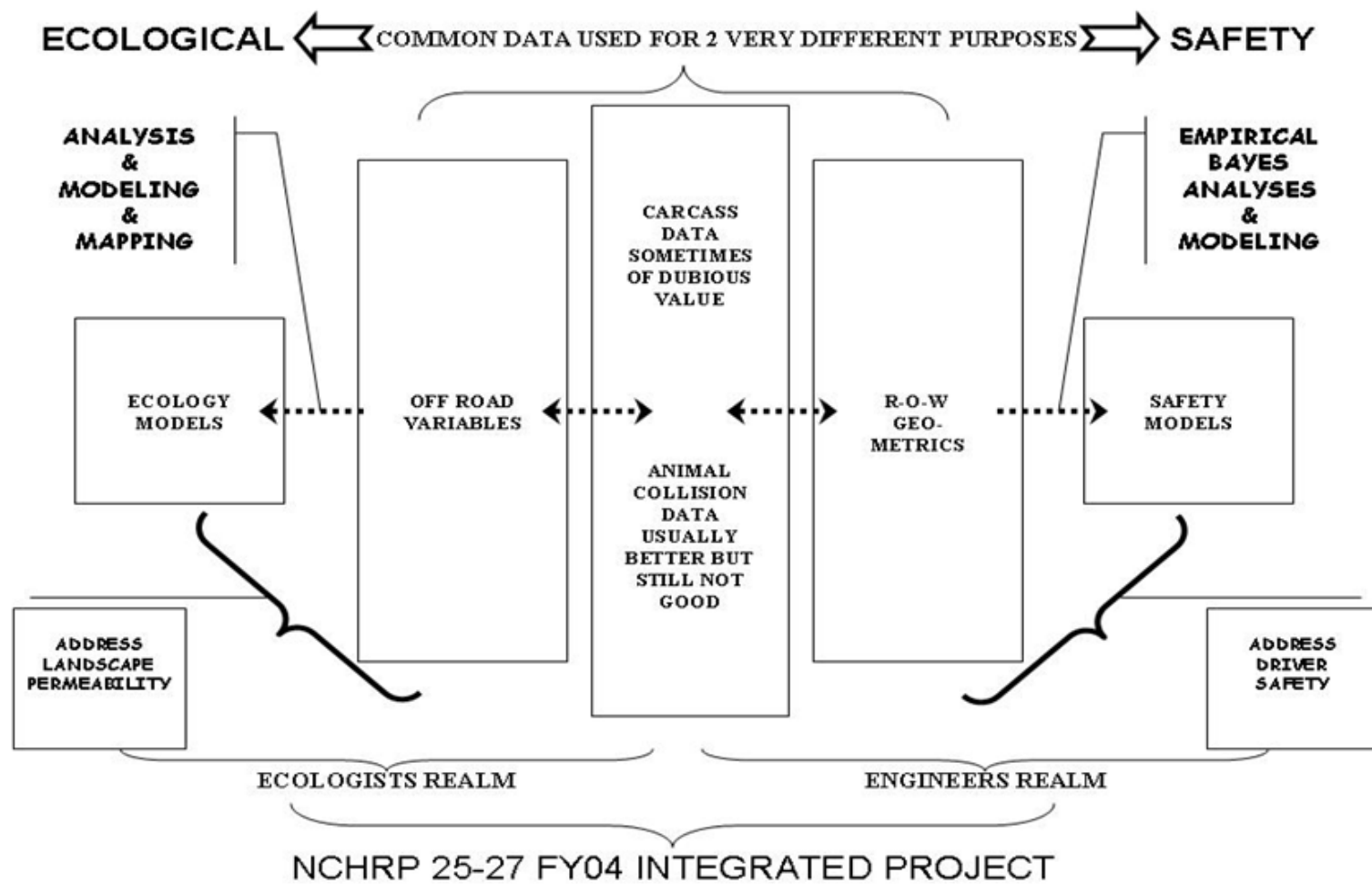
Figure 1: Vision for the NCHRP 25-27 FY04 project

Note: As a convention, we have used the term wildlife vehicle collisions (WVC) rather than animal vehicle collisions (AVC), because we are specifically dealing with only wildlife species and not domestic animals or livestock that may be hit by vehicles on the road. All other permutations, including for example, Wildlife Crashes, WVC carcass collection, and Wildlife Collisions are used rather than using the more generic word "animal".

CHAPTER 2: PHASE I SUMMARY

LITERATURE SEARCH AND DATABASE (2.1)

Members of the team continually research literature pertaining to wildlife and roads in respect to animal–vehicle collisions. The references are updated to the online database of literature for this project on a regular basis. The majority of these references are annotated with key words and a description of the research results and quality of methods and data. As of 31 May 2006, over 300 entries exist in this database. The majority of these articles and papers are stored electronically on the computers of team members. To the extent that we can legally present these papers, they will be available on the website for use in the decision tool and other queries.

THE STATE OF THE PRACTICE AND SCIENCE OF WILDLIFE CROSSINGS IN NORTH AMERICA (2.2)

Lead:

P. C. Cramer, J.A. Bissonette

Abstract

In this paper, we present results of the North American telephone survey conducted to document virtually all wildlife passages created in cooperation with United States Departments of Transportation and Canadian Provincial Ministries of Transportation. We also introduce the concept of a permeable landscape as a basis for understanding the need to install multiple crossings for multiple species that inhabit an ecosystem. Our telephone survey included participants employed by state/provincial and federal agencies, private organizations and companies, and academic institutions. More than 390 respondents answered questions concerning wildlife crossings, planning for wildlife and ecosystems, wildlife-vehicle colllision information, and past, current, and future research activities related to roads and wildlife. The survey revealed over 550 terrestrial and 10,000 aquatic crossings in North America. These passages are found in 43 of the United States and ten Canadian provinces and two territories. Trends found in the practice of wildlife crossings include an increase in the number of target species in mitigation projects, increasing numbers of endangered species as target species for mitigation, increasing involvement of municipal and state agencies, increasing placement of accompanying structures, and a continent-wide neglect in maintenance of these structures.

The trends in the science of wildlife passages include a tendency for a greater percentage of new passages to be monitored for efficacy, a broadening of the scope of research in terms of the number of species considered, an increase in the length of monitoring time, an increase in the number of scientific partners, and increasingly sophisticated research technology. We document several projects in North America where a series of crossings has been, or will be, installed to accommodate a suite of species and their movement needs, thus promoting permeability. A list of general

scientific recommendations is presented to assist in the research, design, placement, monitoring, and maintenance of crossings.

Introduction

How well are we mitigating roads for wildlife? Strides in the science and practice of transportation (road) ecology have become exponential over the past decade, yet overall we know little of what has been accomplished and how these efforts are helping to make the roaded landscape more permeable for wildlife. In this paper, we present the concept of permeability, the overall efforts and trends in North America to mitigate roads for wildlife with wildlife passages, and trends and future needs in the practice and science of mitigating roads for wildlife.

Wildlife need to move to meet their basic survival needs, and there is an imperative to evaluate our current mitigation efforts along transportation corridors for their ability to help multiple species meet these needs. Whether looking at phenomena such as long distance caribou migrations, butterfly movements, fish returning to inland waters to spawn, or frogs trying to get to the nearest pond to lay eggs, there is a continuous theme of daily and seasonal movement throughout the entire life cycle of all faunal species. With our ever increasing 'roading' of the natural landscape, we cause obstacles to both short and long distance movements in both aquatic and terrestrial species. To better accommodate species' needs to move freely, mitigation measures need to be brought into transportation programs and project plans from the very inception of long-range plans, and to continue into the daily maintenance of roads and railways. In North America we have been installing such measures for wildlife along roads since 1970. In the interim, we have researched, designed, built, and monitored these crossings. While we have learned volumes, there is a need to better communicate current knowledge and build on our successes.

One major theme in effective mitigation measures and in current scientific thinking of transportation corridors and wildlife is the need for restoring permeability. As researchers study movement needs of different species in a variety of ecosystems, we are becoming more cognizant of the fact that our efforts to help one or two focal species move under and over roads may not adequately compensate for the lack of permeability roads and railways cause for the entire suite of species in an ecosystem. Permeability is an essential factor to consider in our efforts to accommodate wildlife in transportation corridors. Achieving permeability begins when several different types of mitigation measures, such as different types and sizes of crossings, are placed throughout the course of the transportation corridor so that most species and many individuals of nearby populations are able to use these crossings. These crossings would be placed in sufficient quantity so that most species, in both day-to-day and specific seasonal movements, would be able to find and use crossings within a single home range. It is the intent of this research to document North American efforts to mitigate the roaded landscape for wildlife movement, and to highlight projects where multiple passages appear successful in achieving permeability for wildlife.

Research Approach:Methods and Data

The Telephone Survey

A telephone survey was administered to professionals in transportation and ecology in all 50 United States, and most Canadian provinces and territories. The survey consisted of 25 questions centered on three areas of interest: wildlife-road mitigation measures, wildlife-vehicle colllision data, and transportation planning. Candidates for interviews were selected from contact information on individual state project entries on the U. S. Federal Highways Administration 'Keep It Simple' website, through consultation with U.S. Federal Highways Administration representatives, from lists of attendees of the Transportation Association of Canada (TAC) meetings, and from personal contacts of team members. These individuals were given approximately five opportunities to respond to requests for interviews through emails and phone calls before a new contact was pursued. Once the contact person was introduced to the survey, she or he was given the opportunity to refer the survey or specific questions to someone more knowledgeable. A goal was to interview a minimum of two people within every state and province in an effort to best represent state Departments of Transportation (DOTs), provincial Ministries of Transportation (MoTs) and the state or federal wildlife agency. Interviewees not only provided answers to the survey questions, but were also asked to provide reports, articles, and photos of their mitigation measures and DOT sponsored research projects that focused on how wildlife move with respect to roads. The survey was conducted from July 2004 through March 2006.

Crossing Structure Definition

An important component of this research was in defining a crossing structure. For this survey, a crossing structure was defined as a new or retrofit passage over or below a roadway that was designed specifically or in part, to assist in wildlife movement. Culverts and bridges already in place when fencing was installed to lead animals to pre-existing structures were not considered crossings. These structures were only defined as crossings if they were altered with such methods as weirs for fish passage, shelves for terrestrial wildlife, rip rap removed for wildlife movement, or other such actions.

Findings and Results

Survey Participants

As of May 2006, 396 people have participated in this survey. The number of participants per state/province varied from one to 44 (Figure 2). States or provinces with small representation (less than 5 interviewees) were able to provide data from central resource personnel, while states with multiple interviewees are often states where information is not available within central headquarters of the state DOT, and biologists-planners within each district or region of a state were called for their knowledge of crossings in their domains. The professional titles of respondents included engineers, planners, biologists/ecologists, Geographic Information Systems (GIS) analysts, and researchers. Respondents included representatives from every state DOT, most Canadian MoTs, most state wildlife agencies, the U. S. Federal Highway Administration, the U. S. Fish and Wildlife Service, the U.S. Forest Service, researchers from universities and the U. S. and Canadian National Park Services, representatives of Native American tribes, several non-profit natural resource organizations, and consulting companies.
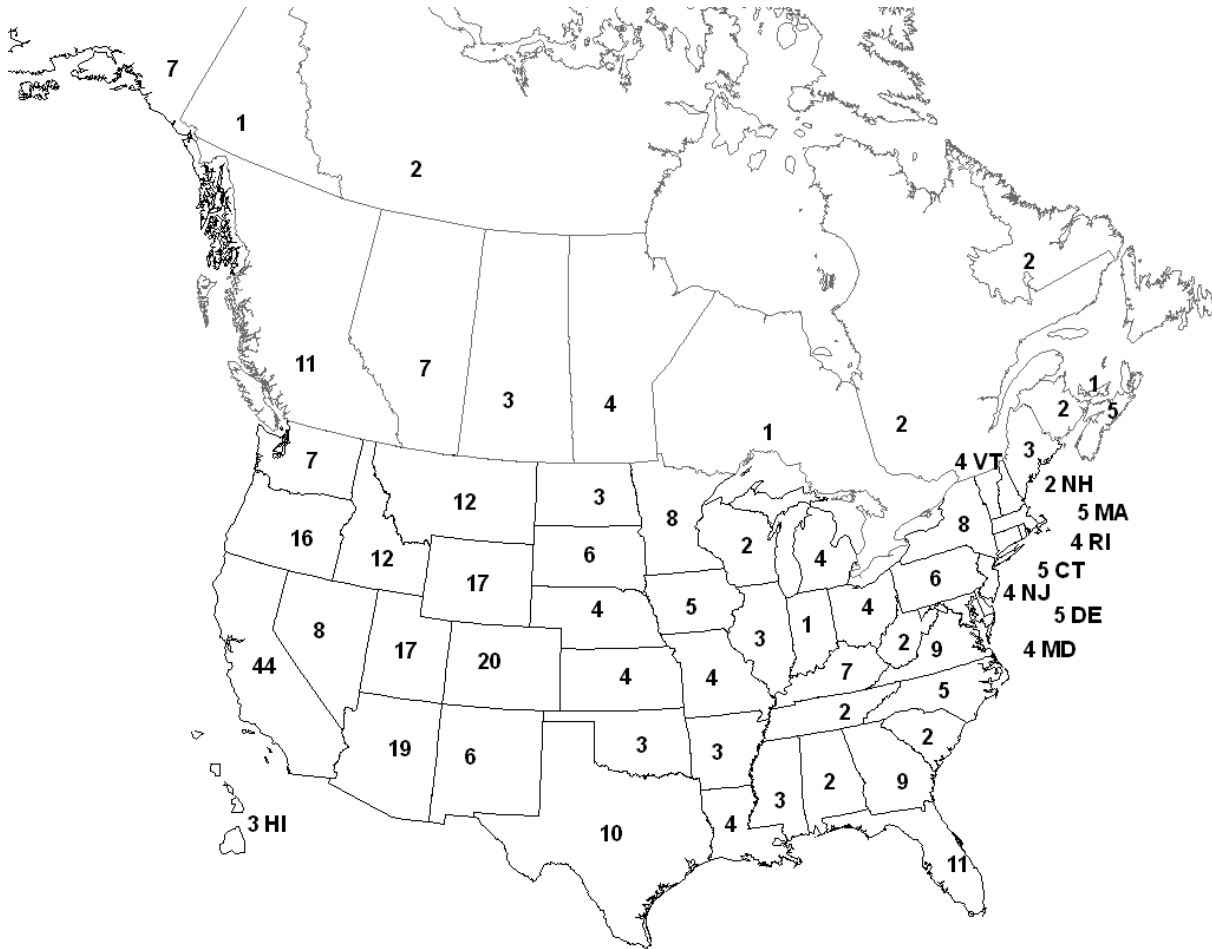
Figure 2: Number of survey participants per state, province and territory

Total crossings

The total number of wildlife crossings in North America can be considered a moving target, the number depends on who you ask, when the question is asked, how you define them, and if you consider aquatic crossings as well as terrestrial ones. There are a minimum of 400 terrestrial underpasses and four overpasses in the United States. In Canada there are a minimum of 140 terrestrial underpasses and 3 overpasses. Aquatic passages are less likely to be recorded as accurately as terrestrial passages. There are a minimum of 500 aquatic passages (installed solely or in part for aquatic fauna) in the United States, and roughly 10,000 or more aquatic passages placed throughout Canada. When combined, there are a minimum of 550 terrestrial passages and 10,500 aquatic passages in North America (Figure 3). Further analyses will be conducted to specify the number of crossings created for specific target species and the number of crossings per type of structure, such as small culvert, extended bridges, overpasses, etc. These results and the quantitative representations of the trends mentioned in the next section, such as changes in target species over time, will be included and discussed in the final report.
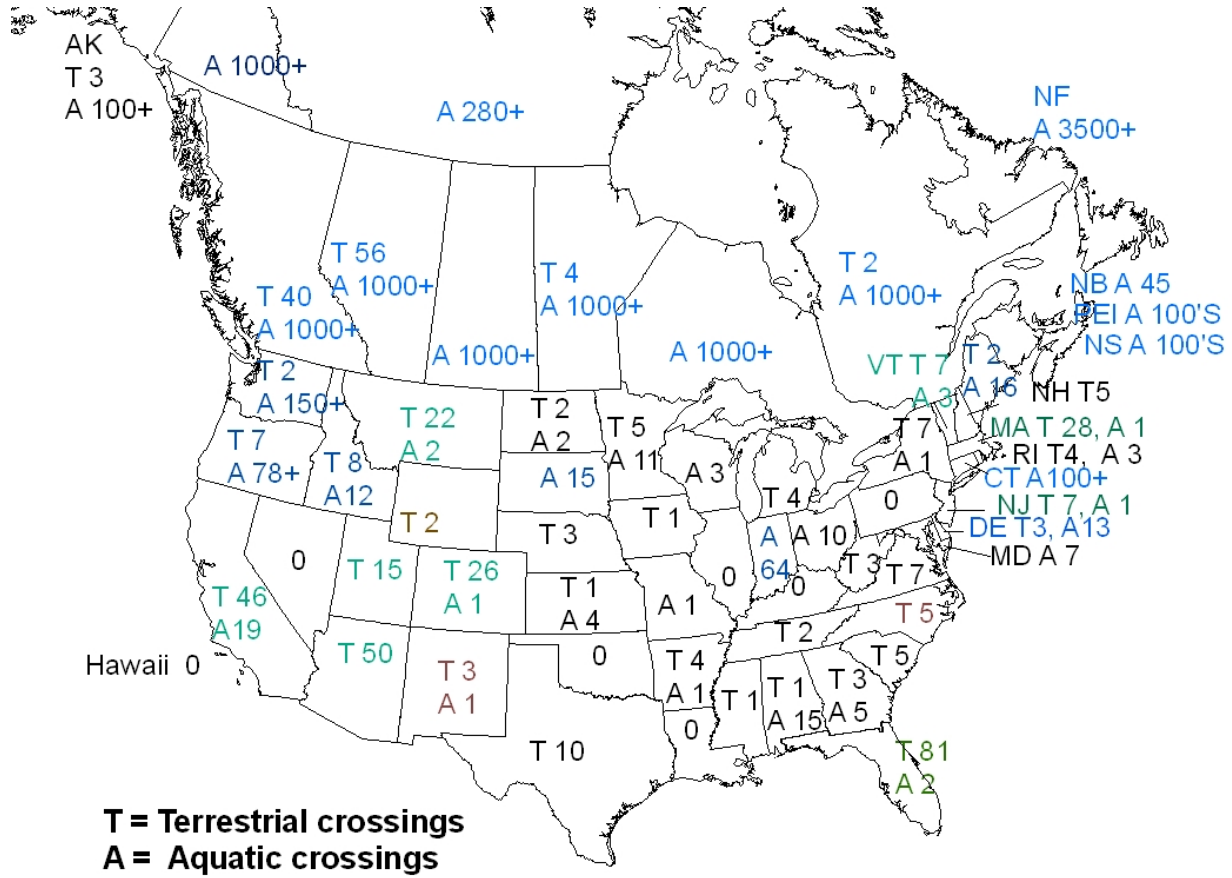
Figure 3: Number of terrestrial and aquatic wildlife crossings in North America

Interpretation, Appraisal, and Applications

Trends in Practice

A number of trends in the development and practice of wildlife passages over the past four decades became apparent in the analyses of the data:

1) Over time, there has been an increased number of target species considered in mitigation projects

2) There are increasing numbers of endangered species as target species for mitigation

3) There is a continued increase of involvement of many agencies and organizations in the planning and placement of crossings

4) An increase in the placement of accompanying structures

5) A continent-wide neglect of maintenance of these structures

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The trend of increasing numbers of target species for wildlife crossings stems from the fact that the earliest wildlife crossings, which were installed in the 1970's, were for white-tailed deer (*Odocoileus virginianus*) and mule deer (*Odocoileus hemionus*). These include the first documented underpass/culvert crossings in Colorado for mule deer (1970),[195] and New York (1970) for white-tailed deer. The first overpass in North America was created for mule deer and elk (*Cervus elaphus*) in Utah in 1975. During the 1980s, Florida became the continental leader in the number and variety of types of wildlife passages, and began the trend of multiple species crossings with the installation of 24 underpasses and 12 culverts for wildlife during the expansion of I-75 from Naples to Fort Lauderdale.[99,100]

Florida also began the trend in creating passages for endangered species of wildlife with its focus on passing wide-ranging federally listed carnivores, such as the Florida panther (*Puma concolor coryii*)[150] and Florida black bear (*Ursus americanus floridus*),[202] under roads that bear ever-increasing numbers of motorists. Carnivores are not the only type of endangered species that are targets for wildlife crossings. Endangered ungulates such as the Key deer (*Odocoileus virginianus clavium*)**Error! Reference source not found.** in Florida, endangered small mammals such as Preble's meadow jumping mouse (*Zapus hudsonius preblei*) in Colorado, endangered amphibians such as the arroyo toad (*Bufo californicus*) in California, reptiles such as the desert tortoise (*Gopherus agassizii*)[31] in California and Arizona, birds such as the pygmy owl (*Glaucidium brasilianum cactorum*) in Arizona, and invertebrates such as the Karner Blue butterfly (*Lycaeides melissa samuelis*) in New York have all been targets of mitigation measures across and under roads. Future crossings will continue to be influenced by the presence or potential presence of species in some status of protection, from kit foxes (*Vulpes macrotis mutica*) in California, lynx (*Lynx canadensis*) in Colorado, Oregon, Montana, Minnesota, and Idaho, ocelot (*Felis pardalis*) in Texas, grizzly bear (*Ursus arctos*) in Montana and Alberta, Blanding's turtle (E*mydoidea blandingii*) in Minnesota, the diamondback terrapin (*Malaclemys terrapin*) in Delaware and Georgia, Salt Creek Tiger beetles (*Cicindela nevadica lincolniana* Casey) in Nebraska, the Grizzled Skipper butterfly (*Pyrgus malvae)* in Ohio, to the salmonid species of fish in Washington, Oregon, and California. These and other species' needs to move throughout roaded landscapes, the laws that protect them, and the oversight and involvement in transportation projects by the U.S. Fish and Wildlife Service contribute greatly to increase the number of crossings existing and planned for North America.

There is also an increase in the number of agencies involved in the planning and placement of wildlife crossings. The more traditional model was for a state or provincial DOT/MoT to work with the state/provincial wildlife agency in determining the species present and the necessary mitigation measures. Increasingly, the U.S. Fish and Wildlife Service in the United States has become involved in planning and placing wildlife crossings as we become more aware of the needs of federally listed endangered and sensitive species of wildlife and plants. The U.S. Federal Highways Administration has also become more involved in the creation of mitigation measures and in helping to urge their design early in the planning process. As roads are widened and otherwise upgraded in rural landscapes, we find that federal natural resource agencies, such as the U. S. Forest Service, have become involved in determining the need for and placement of wildlife crossings. This has happened in Canada as well, with the Parks Canada agency

largely responsible for the installation of 24 wildlife crossings under and over the Trans Canada Highway. As cities grow into areas that were until recently largely rural and wild, we see the planning and placement of wildlife passage in concert with city and county entities. The Pima County (Arizona) experience with wildlife crossings is a leading example of how a county entity has helped in researching, designing and placing wildlife crossings for suites of species near Saguaro National Park, and how they have placed what may be the first bird crossing in North America for the pygmy owl.

Members of First Nations and Native American tribes across the continent are leading the trend of non-governmental agencies involved in mitigating roads for wildlife. There are examples of how Native peoples have insisted on protecting and helping wildlife pass under and over roads. These included the grass roots efforts of the Tohono O'Odham Indians in Arizona to bring the community together to install fencing to help desert tortoises pass through existing culverts. Through monumental efforts, the Salish-Kootenai tribe works with the U. S. government and Montana DOT to mandate and help design the future 42 impending passages on U.S. 93 which passes through the Flathead Reservation in Montana. As this trend continues, we will see an increase in grass roots efforts within smaller entities that are learning from the larger groups how to tackle the problems of roads and wildlife.

There is also a trend toward increasing efforts to include several accompanying structures along with underpasses to help wildlife navigate the necessary pathways to getting off the roadway. From the first wildlife underpasses, fences were and still are, placed along the road leading to the majority of underpasses to encourage wildlife to use the structures. Innovative measures today also include placing large boulders near the approach to passages to help guide larger wildlife to the crossing. The problem of animals entering the roadway at the end of the fence, or finding or creating holes in the fence to enter the roadway quickly became apparent and created a need for wildlife to escape the road Right-of-Way (ROW). In the 1970s, escape gates were designed, probably originating in Colorado,[194] where deer or elk could escape the fenced roadway to the wild area by pushing their weight against tines in a specific gap in the fence. In the 1980s and 1990s, escape, or jump-out, ramps were developed over several western states to help wildlife, specifically deer and elk, escape the road.[28] These ramps are continually being refined and tested across western North America, and are used by deer, elk, and bighorn sheep (*Ovis canadensis).* Efforts are also underway to 'coax' animals to passages, including water guzzlers, which collect water in dry climates and encourage wildlife to the passage (in California and Arizona).[74] Passages are also baited for the first post-construction years. Wildlife shelves are placed in existing culverts and passages to encourage small and medium animal use when the passages are wet.[93,94] Shrubs, logs, woody debris, and tubes have been placed for small animal passage. Shrubs and trees have been planted to lead wildlife to the entrances of passages (Black bear passage in Florida).[202] Wildlife walls under 2 meters high have been placed to funnel smaller species such as reptiles and amphibians to crossings (Paynes Prairie in Florida).[71] Turtle, tortoise, and amphibian fences have been designed to direct these smaller species to crossings.[31,131] The future of wildlife crossings will no doubt include continued innovative methods, such as vegetation and median berms to direct airflow up over the road and traffic, helping insects and birds fly over the roadway dangers.

Although we have many positive examples of efforts to mitigate roads for wildlife, there are also examples of other efforts that have not proven successful. The two most often cited reasons for passage failures are passages that are not placed in the correct place, and that passages and accompanying fence are not maintained. The latter reason is preventable as a simple planning and staffing effort. Wildlife crossings are placed in dynamic landscapes; rivers and ephemeral water sources bring debris into structures, snow pulls down fences, and wildlife and human activity create holes in fences or degrade crossings. Additionally, human activities make passage by wildlife extremely difficult due to vehicle use and parking in passages, camping in passages, domestic dog usage and marking of passages, or shelter for homeless people. Although there is a plethora of ways passages require maintenance, a common theme across the continent is that passages, fences, and accompanying structures are placed, but inadequately maintained, if maintained at all.

Examples of Multiple Crossings That Promote Permeability

The overall trend of increasing numbers of target species for wildlife crossings is illustrated by several projects which contain or will contain series of crossings for suites of species. These projects include the Trans Canada Highway in Banff National Park, Alberta, which has 24 crossings in place and eight more planned over 45 kilometers. These crossings include overpasses, underpasses, and culverts for species ranging from small mammals to grizzly bears and elk.[52,57] In Montana, U.S. Highway 93 has 19 current crossings of various size south of Missoula, and over 60 more crossings planned from Sula north to Polson. These crossings are intended for suites of species and several have already been researched to find that they are working for the intended species.[93,94] In Arizona, the same U.S. Highway 93 has dozens of crossings for species ranging from desert tortoise to bighorn sheep, with dozens more planned. In Florida, the first series of crossings were built in 1982 along Florida's Alligator alley for the Florida panther and the accompanying suite of wildlife from the ecosystem such as Florida black bear, bobcat (*Lynx rufus*), deer, alligators (*Alligator mississippiensis*), wading birds, fox (*Vulpes vulpes, Urocyon cinereoargenteus*), raccoon (*Procyon lotor*), opossum (*Didelphis virginiana*), fish, and others. Thirty-eight crossings, from large underpasses to culverts were established over 64 kilometers,[100] allowing for a greater degree of permeability than most established crossings. Vermont as a whole is an example of how several simultaneous projects help create a permeable landscape in several different regions. Road projects to watch in this state include Route 78 along the viaduct over Missisquoi National Wildlife Refuge, and the Bennington Bypass on US 7 and State Highway 9.

Trends in Science

The state of the science of wildlife passages was assessed from reports submitted by telephone survey participants and a concurrent review of the literature, which amassed over 200 reports and papers. Trends in the science of roads and wildlife indicate:

1) A tendency for a greater percentage of new passages to be monitored for efficacy

2) A tendency for a broadening of the scope of research in terms of the number of species monitored for use of passages

3) Increases in the length of time for monitoring

4) Increased numbers of participants in research projects

5) Increasingly sophisticated research technology

Monitoring of wildlife passages began in 1970 with one of the first underpasses for wildlife in North America. This underpass was placed near Vail Pass along I-70 in Colorado, and was monitored for mule deer use.[195] This level of monitoring was rare for passages placed in the following two decades. Since 2000, there has been an increase in the pre-construction monitoring of new passages. During the past fifteen years, there have been an increasing number of studies that considered multiple species near roads, thus broadening our knowledge base and mitigation efforts. Research projects today tend to monitor species use of passages for greater lengths of time than in 1980s and 1990s studies, with monitoring efforts extending to several years post-construction. Finally, the study of wildlife crossings has included more scientific partners than in past decades, including state wildlife agencies, federal natural resource agencies such as the U.S. Forest Service, the U.S. National Park Service and Parks Canada, university researchers, consulting companies, municipal biologists, and the indirect input of many more scientists who help to develop state-wide connectivity analyses. These analyses are becoming increasingly important in the placement of crossings. The advancing sophistication of technologies such as GIS, infra-red video cameras, and Global Positioning System (GPS) collars have greatly facilitated aspects of scientific research of wildlife in relation to roads, and have helped to make mitigation structures more accurate in placement, dimensions, and overall design.

As an extension of an evaluation of wildlife crossing science, a review has begun of studies evaluating the use of wildlife passages. Approximately 25 scientific studies assessing the efficacy of 70 terrestrial wildlife passages across North America found that all passages passed wildlife, and 68 of the passages passed the target wildlife species. A further review of these documents will be included in the final report.

Conclusions and Suggested Research

Best Projects to Watch

While every state and province in North America is at a different step along the way to creating more permeable roads for wildlife, we would like to mention a few of the more progressive projects and programs across the United States and Canada that highlight what can be done on a continental scale as far as truly mitigating roads for wildlife. Currently, the most extensive mitigation efforts in the United States, occur on U.S. 93 which runs from just northwest of Phoenix, Arizona, through Nevada, into Idaho, through Montana and into Alberta. Dozens of crossings are already placed on this roadway to facilitate movement by desert tortoises and ungulates in Arizona, and for fish, and small and large mammals in Montana. In Montana alone, twenty crossings specifically for large mammals are in place. This highway will have an estimated 50 more crossings in Montana, including one overpass, and dozens of crossings in Arizona, for a total of over 125 crossing along its reach.

The most heralded in the media and the most published in the scientific literature, are mitigation measures employed in Banff National Park on the Trans Canada Highway, with 2 over passes and 22 underpasses in 45 kilometers, and 8 more planned along the

next stage of construction.[163] One of the best scientifically designed mitigation and research projects is that of State Road 260 in Payson Arizona on the Tonto National Forest. This mitigation project was designed, constructed and monitoring in joint collaboration with the Arizona DOT, Arizona Game and Fish, and the U.S. Forest Service, among others. Seventeen bridges have been or will be placed along the highway so that elk, mule deer and other wildlife can cross safely underneath. The biologists working on this project have done an exemplary job of monitoring wildlife use of these passages through utilization of GPS collars, video surveillance systems, and road-associated mortality data.[72,74,102] In the future, we believe Colorado's Mountain Corridor project for I-70 through the Rocky Mountains[140] with a possible overpass, and Washington's I-90 Snoqualmie Pass project,[238] will showcase innovative methods of crossings with as many as a dozen new crossings per project. In the east, Vermont is another state to watch. This state has made it their motto to go beyond the regulations and do the very best they can for wildlife. Vermont has at least nine existing crossings, and at least a half dozen more scheduled for the next five years. Many of these new crossings will be series of crossings for multiple species. Last but not least, Florida which pioneered wildlife passage efforts, will continue to construct crossings, with thirty more planned for the next 10 years, including an overpass near Orlando.

General Recommendations for Crossings

A part of research for this project, we have begun examining the general recommendations for installing wildlife crossings. While other authors make specific recommendations in their publications, we would like to review the consistent trends that appear in the literature, scientific talks, and in our telephone interviews, with reference to what the state of the science reveals about wildlife crossings.

What we know about the science of crossings:
- Bigger is better
- Cover is important at the ends of passages for some species, while others need cover inside the passage
- Deer require a larger openness ratio than most other mammals
- Some deer in urban-suburban situations will use pre-existing structures that are far smaller than what their counterparts in more natural landscapes will use, for example a culvert less than 2 meters high with a 90 degree angle
- Ungulates and carnivores may prefer different types of passages, for example, ungulates may prefer overpasses while certain carnivores prefer underpasses[57]
- Light in the middle of the tunnel/passage is helpful for passage of many species from salamanders to deer, but may not be welcome by certain carnivores
- Noise reduction is beneficial
- Reduced human usage, in general, especially at night, is important
- Pathways or shelves for wildlife to pass through riparian underpasses are working for large animals like large deer and elk, to smaller ones like mice and voles
- Considerations concerning special conditions for the target species or suites of species is necessary, for example:
  - o Amphibians need tunnels that are wet and cool

- o Small mammals need cover in the form of logs, rocks, and bushes
- o Pronghorn need open, natural conditions to the extent possible
- o Fish, especially juveniles, need culverts that do not rise more than two body lengths above natural water levels. They need low natural volume in culverts, with culvert bottoms approximating natural riverine conditions. Weirs may need to be provided
- Include accompanying mitigation such as fencing and jump off- escape ramps
- Protect both sides of the passages for conservation in perpetuity
- Passages need to be seen by wildlife as they approach the roaded areas. Passage placement in a straight line of sight works better than those placements below or above the approach levels.
- Involve local biologists in all phases of project
- Adaptive management works: monitor and improve future designs based on monitoring results
- To strive for true permeability, provide several different types of crossings, or adapt crossing for suites of species by providing cover, shelves, small tubes, culvert within a culvert, etc.
- Maintain passages and accompanying mitigation, especially the bottom of passages in riparian areas, and holes in fencing
- Monitor passage use for at least 3 years after construction: it takes wildlife at least 2 years to adapt, especially if they use the area only for seasonal migration

Wildlife crossings and road ecology have evolved dramatically in the 36 years since the first crossings were installed in Colorado and New York. Wildlife and roads will continue to be an issue for the scientific and practice communities as well as the public. In fact, a recent survey of over 1,000 registered voters in the United States found that 89% of those surveyed felt that roads and highways were a threat to wildlife.[242] It is in the best interest of wildlife and ecosystems that we, as road ecology professionals, maintain high standards in our profession, to promote functioning wildlife passages across North America. This includes developing the knowledge necessary for installing mitigation measures that create a more permeable landscape where many different species of a range of mobility and sizes can cross over and beneath our transportation corridors in their daily and seasonal movements. This goal of greater permeability will take dedicated work on the part of scientists and practitioners to include wildlife passages in the earliest of stages of long-range transportation programs, passages at the project level, passage maintenance during routine maintenance operations, as well as scientific research on the success of passages in meeting stated goals and objectives. Communication among those interested in passages, as well as those not typically involved in ecosystem concerns, such as planners, engineers, and administrators, should be proactive and collaborative. It takes the efforts of a community open lines of communication. We can be proud of the over 550 terrestrial and more than 10,000 aquatic passages that have been placed in North America. As we plan for the future, we can learn from both successes and failures and from those most proactive in placing mitigation measures. We can build on the current level of awareness among the profession and the public, and create a continent-wide system of passages. It is a vision that will take time and requires the collective efforts of all stake holders.

PRIORITIES IN RESEARCH AND PRACTICE (2.3)

Lead:

P. C. Cramer, John A. Bissonette

Abstract

We developed a list of gaps and priorities based on the team's knowledge of current research and practices in road safety and ecology and then asked approximately 500 professionals across North America to rank these priorities. Our objective was to determine where additional research, field evaluations, and policy actions were needed in order to help maintain or restore landscape connectivity and permeability for wildlife across transportation corridors, while also minimizing wildlife-vehicle collisions. This list of priorities was initially reviewed and annotated by dozens of practitioners and researchers in North America and then ranked and annotated in surveys by attendees at two conferences/workshops. The final survey was refined and posted on the internet in April of 2006, where potential participants were invited to rank priorities and to ask other qualified transportation and ecology professionals to take the survey. The final list of ranked priorities was the result of the participation of over 400 professionals from across North America.

The top five priorities were ranked as follows:

1) Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process

2) Better understand the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information

3) Combine several animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than relying on just one method

4) Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out

5) Develop alternative cost-effective wildlife crossing designs and the principles they are based on

The priorities were developed and ranked in order to help direct research, policy, and management actions across North America that address the issue of reducing the impacts of the roaded landscape on wildlife and ecosystem processes.
The results were also tabulated for individual states and provinces where eight or more participants resided. These state/provincial rankings were compared for differences with the continental priorities, and the results were sent to participants residing in those states/provinces. All participants were sent the overall continental survey results. It is expected that these ranked priorities can help direct planning, policy, research, and management actions across North America that address the need for wildlife and natural processes to move across the roaded landscape and the need for safe conditions for

motorists. For example, the top five priorities can lead agency personnel in directing early planning for wildlife in transportation planning, help encourage the installation of suites of mitigation measures for wildlife, promote the use of connectivity analyses in transportation planning, and the development and use of alternative cost-effective crossing designs. Researchers can see the need to design studies that address our need to better understand the dynamics of animal use of mitigation structures, and disseminate this information. Additional priorities can help raise awareness for the need for better communication among agency personnel and the public, and help states to initiate standardized guidelines and methodologies involved in wildlife crossings and animal-vehicle collisions. Organizations working at the national level may use these guidelines to help direct policy initiatives as well.

Introduction

The field of transportation (road) ecology is swiftly developing and is practiced throughout North America and internationally without a parent organization or society to help guide research and practice. As a result, attempts to document and mitigate transportation effects on wildlife can appear to promote scattered and duplicative efforts. National and continental efforts are underway to document knowledge, accomplishments, and future actions, and in particular how to mitigate the negative effects of transportation corridors for wildlife.[80,210,62,181] To determine future activities, a North American consensus regarding top priorities for research and practice would prove most helpful. The research reported in this section is an effort to create a prioritized list of actions in safety and ecological research and practices to help mitigate the negative impact of roads on wildlife in North America. Our objective is to determine where additional research, field evaluations, and policy actions are needed in order to help maintain and restore landscape connectivity and permeability for wildlife across transportation corridors, while also minimizing wildlife–vehicle collisions. It is our hope that these priorities will help guide future planning, policy, research, and management actions across North America.

Research Approach: Methods and Data

Setting Priorities

The creation of the list of gaps and priorities in transportation research and practice with respect to wildlife began with a review of the pertinent literature. A list of approximately 120 priorities was generated by the research team and then combined to create 25 highly-ranked priorities. The initial priorities were sent to 31 professionals in federal and state agencies and academic institutions across North America for review and editing. Thirteen reviews of the document were received and information and edits from these reviews were incorporated into the priorities, along with comments from the National Academies' NCHRP 25-27 Review Panel.

Creating the Survey Instrument

During the development of an effective questionnaire, the priorities were ranked and annotated by 27 attendees of the Wildlife Crossings Workshop in Payson Arizona

that was sponsored by the Southern Rockies Ecosystem Project, the Arizona Department of Transportation, and the Arizona Game and Fish Department. These suggestions were incorporated into the survey instrument, and the survey was re-organized into a more concise and easily understood document. For a second iteration, the updated survey was presented to the attendees of the Deer-Vehicle Crash Workshop in Madison, Wisconsin. Eighteen participants submitted surveys with further suggestions for priorities and suggestions for improving the survey instrument. Their comments were incorporated into a final version that was presented as an on-line-internet survey. The survey instrument was based on Dillman's[70] methods for email surveys, and advice from R. Krannick (personal communication, Sociology Department USU, 2005). Participants were asked to rank the priorities on a scale of zero (no priority) to 10 (top priority), and an option for 'Not Enough Information' based on three criteria:

1) Cost-effectiveness – are the returns on the investment of money for research and development worth the cost?

2) Urgency – Does this priority need the most immediate action based on development pressures, safety issues, species' survival, transportation projects, and political climate?

3) Overall effects – If this priority were accomplished, would it have far-reaching results across geographic, political, disciplinary, and ecological boundaries?

Priorities were presented in two sections, with 11 priorities listed under practice, and 14 priorities listed under science. Participants were instructed to rank all priorities as they should be ranked overall, not within these two categories. The priorities were placed into two categories to help direct management actions separately from research actions. Each priotiry was ranked from 1-10, thus allowing for multiple indentical values among a participant's priorities.There were four optional questions at the end of the survey pertaining to the participant's job title, area of expertise related to transportation ecology, the state or province of employment, type of employer, and email address. Participants submitted the survey by clicking on a 'Submit Survey' button at the bottom of the page.

Selection of Participants

The participants for the survey were selected using non-random methods intended to select people with knowledge about transportation and wildlife issues in North America. The largest set of potential survey respondents was taken from the pool of participants in the telephone survey we conducted as part of this NCHRP research project. They included persons involved in data management of wildlife-vehicle colllisions (WVC) and carcass removal data who worked for Departments of Transportation (DOTs) and Ministries of Transportation (MoTs), the U.S. Federal DOT Highway Administration, state wildlife agencies, the U.S. Fish and Wildlife Service, the Bureau of Land Management, U.S.D.A. Forest Service, the U.S. National Park Service, Parks Canada, and consulting companies. The pool also included academic and federal research personnel involved in road ecology and road safety analyses. The pool of telephone survey participants came from an original list of names taken from projects listed on the U.S. Federal Highway Administration's website titled, "Keeping it Simple:

Easy Ways to Help Wildlife Along Roads,"[85] the list of participants in the International Conference on Ecology and Transportation for the conferences in 2001 and 2003,[127,128] and recommendations from key Federal Highway Administration personnel involved in wildlife mitigation across the country. Canadian contacts were compiled by research team members and from lists of attendees of the Transportation Association of Canada (TAC) meetings. The goal of drawing from those resources was to make contact with practitioners and researchers involved in road ecology as well as individuals from state and provincial DOTs and MoTs who work with transportation and wildlife projects. Those initial contacts led to many other contacts across North America who potentially could contribute to the telephone survey on wildlife and roads.[66] The members and friends of the Transportation Research Board's Task Force on Ecology and Transportation were also invited to participate in the survey. The initial 497 invited participants were encouraged to pass the survey on to peers in their agency and profession who had knowledge that would assist them in ranking these priorities. This led to a snowball sample of a much larger population of unknown size.

Delivering the Survey

The potential survey participants were notified of the forthcoming survey during the last three days in March 2006. A second email was sent a week later with a request to take the survey online or to print the survey and send us a hard copy. Potential participants were given 17 days to take the survey before it was closed. Four days prior to the closing of the survey, all participants who had not taken the survey, or who had taken the survey but did not give their email addresses, were sent a final reminder. During the last two days of the survey, an additional 17 potential Canadian participants were included in the survey mailings, and survey availability was extended for one week. The survey was officially closed 28 days after it was opened.

Statistical Analysis

Survey results were analyzed using the SPSS software program. [220] Analyses of variance (ANOVA) were conducted for comparing mean values of each priority as rated by different classes of survey participants. The Levine statistic was first run to test for homogeneity of variance. When variances among the different mean values of a priority among the different participants were not equal (as shown by a significant Levine statistic), the ANOVA analysis was not used, and the Welch test, which accounts for unequal variances was used to test for significant differences in priority means. F-tests were used in cases where means met the equal variances assumption of ANOVA. The Games-Howell post hoc test was used to determine the locational significant differences between means as shown by the ANOVAs and Welch tests. This particular post hoc test is designed to account for both unequal variances as well as unequal sample sizes.

Findings and Results

Survey Participants

Four hundred and ninety-seven people were initially invited via email to participate in the survey. This was the original pool of invitees. A total of 444 people participated. Of those 444, 388 participants (87.3%) chose to identify themselves by

submitting their email address. Of those 388 email addresses, 254 (65.5%) were identified as members of the original pool of invitees. Response rate of the original invitees who gave their email addresses was 51.5%. The actual response rate is unknown because 56 participants did not submit their email addresses. One hundred and thirty four (30.2%) of the emails given did not match the original pool of invited participants' email addresses. These participants were invited by others to take the survey and thus their participation created what is known as a snowball sample.

Table 1: Number of survey respondents within each U.S. state and Canadian province

United States

State	# Participants	State	# Participants
Alabama	3	Montana	24
Alaska	7	Nebraska	1
Arizona	33	Nevada	2
Arkansas	2	New Hampshire	5
California	73	New Jersey	2
Colorado	22	New Mexico	6
Connecticut	4	New York	9
Delaware	1	North Carolina	10
District of Columbia	8	North Dakota	2
Florida	7	Ohio	4
Georgia	10	Oklahoma	0
Hawaii	2	Oregon	15
Idaho	4	Pennsylvania	6
Illinois	2	Rhode Island	1
Indiana	1	South Carolina	8
Iowa	6	South Dakota	7
Kansas	5	Tennessee	3
Kentucky	4	Texas	14
Louisiana	2	Utah	16
Maine	3	Vermont	2
Maryland	3	Virginia	13
Massachusetts	4	Washington	3
Michigan	3	West Virginia	1
Minnesota	10	Wisconsin	2
Mississippi	1	Wyoming	22
Missouri	5	Unknown	5
		Total # U.S. Participants = 408	

Canada

Province	# Participants	Province	# Participants
Alberta	7	Ontario	7
British Columbia	10	Quebec	3
Manitoba	3	Saskatchewan	1
Newfoundland and Labrador	1	Yukon	3
Nova Scotia	1		
		Total # Canadian Participants = 36	

35

Participants represented all of the United States with the exception of Oklahoma, and the Canadian provinces and territories with the exception of New Brunswick, Northwest Territories, and Prince Edward Island. Of the 444 participants, 403 (90.8%) were from the US and 36 (8.1%) were from Canada (Table 1). Five participants did not indicate their state/province of employment. Participants were asked to generalize the

Table 2: Number of survey participants employed by each type of employer

Employer	Number of Participants
Consulting	37
Federal Natural Resources	70
Federal Transportation	25
Non-profit	23
State Natural Resources	55
State/Provincial Transportation	183
University	45
Unknown	5
Other	1
Total	**444**

Table 3: Professions of survey participants and the number of participants classified for each profession category

Profession	# Participants
Engineers: Engineers/Analysts/GIS specialists-Wildlife-vehicle colllisions	61
Planners	13
Natural Resources–Manager: Managers of resources, esp. wildlife managers	38
Natural Resources-Non-profits: Non-profit personnel & consulting groups	23
Natural Resources-Planner: Planners, program manager, supervisor, coordinator, reviewer of environmental documents, provider of expertise for mitigation, agency personnel with ecological background	187
Natural Resources–Research: Conducts on the ground research, usually wildlife related, agency and university personnel	109
Unknown	11
Other	2
Total	**444**

type of employer they worked for. The majority of respondents (n = 183, 41.2%) were employed by a state/provincial transportation agency. The second largest group of respondents were those that worked for a federal natural resource agency (n = 70, 15.8%). The remaining respondents worked for state/provincial natural resource agencies (n = 55, 12.4%), universities (n = 45, 10.1%), consulting firms (n = 37, 8.3%), federal transportation agencies (n = 25, 5.6%), non-profit groups (n = 23, 5.8%), or other/unknown (n = 6, 1.3%, See Table 2). Each person was asked to list their job title and area of specialty related to roads and wildlife. From these data, each participant was classified into one of seven different profession types: Engineers/Analysts/GIS specialists (n = 61, 13.7%), Planners (n = 13, 2.9%), Natural Resource-Manager (n = 38, 8.6%), Natural Resource-Non-Profit (n = 23, 5.2%), Natural Resource-Planner (n = 187, 42.1%), Natural Resource-Researcher (n = 109, 24.6%), # Unknown (n = 11, 2.5%) or other (n = 2, 0.5%) (Table 3). There were 357 Natural Resource Professionals overall, which represented 80.4% of all participants.

Ranking of Priorities

Priorities were ranked for overall value, and then ranked within practice or research. The rank of a priority was determined by adding all the scores submitted for that priority and calculating the mean value. For example, the top priority to incorporate wildlife mitigation needs early in the planning processes, received a total of 441 rankings, ranging from 1 to 10. Those 441 values were summed, and then the mean was calculated as 8.96, making it the highest ranked priority. Table 4 and Table 5 summarize the results. The top five priorities are:

1) Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process

2) Better understand the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information

3) Combine several animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than relying on just one method

4) Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out

5) Develop alternative cost-effective wildlife crossing designs and the principles they are based on

Priorities by Nation

Practice priorities—The United States and Canadian participants ranked the first three priorities for practice identically:

1) Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process

2) Combine animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than relying on using a single method

3) Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it is to be carried out

Effective communication and collaboration among stakeholders was ranked fourth in the U.S. and fifth in Canada. The use of standard protocols for road kill and animal–vehicle collision data was ranked fourth in Canada. The incorporation of plans and schedules that can be accomplished by maintenance crews was ranked fifth in the U.S (See Appendix A, Table 39).

Research priorities—In ranking the research priorities, the two nations diverged to a greater degree than on ranking practice priorities. Participants from both countries ranked the need to better understand animal use of mitigation structures as the top research priority. The development of cost-effective crossing designs was ranked second in the U.S. and third in Canada. Canadians ranked the need for standardized data collection of road kill carcasses and WVC as their second research priority. In the United States, the third ranked research priority was the need to develop structure designs and guidelines to provide landscape permeability for the full suite of animals in an area. In the U.S., the fourth ranked priority was the need to develop state-based connectivity analyses. In Canada, the fourth ranked priority was the need to develop guidelines for when wildlife mitigation was necessary. For the fifth research priority, U.S. citizens ranked the need to develop protocols for judging the effectiveness of wildlife crossing, while Canadians ranked the need for the development of prototype WVC models to predict priority hotspots (See Appendix A, Table 40).

Priorities by Profession

Practice priorities—Priorities were ranked among the three major classes of participants: Engineers/Analysts/GIS Specialists, Natural Resource Professionals (all types combined), and Planners. Engineers, Planners, and Natural Resource Professionals all had the same top five practice priorities, but ranked differently by profession. Different median values among the professions are noted, with Engineers generally rating each of the top five priorities a lower median value, and Planners rating all five top priorities relatively high median values. Incorporating wildlife mitigation needs early in planning was ranked as the top priority by all professions except by Planners. The median ranked value for this priority among planners was 9.0, similar to the 9.1 value for Natural Resource Professionals. However, Planners rated the need to combine animal-friendly mitigation methods priority as number one (9.23 median value), and early planning as their second highest priority. Engineers ranked the need for effective communication second, while Natural Resource Professionals ranked the need to combine animal-friendly mitigation methods second. Using conservation plans and connectivity analyses ranked alternatively third and fourth among all three professions. Further ranking of the top five practice priorities for the three professions can be seen in Appendix A Tables 41-43.

Table 4: Ranking of practice priorities for transportation and wildlife for North America

Rank within Practice	Priorities for Practice	Rank Overall
1	Incorporate wildlife mitigation needs **early** in the DOT/MoT programming, planning, and design process	1
2	Combine animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than using one method	3
3	Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out	4
4	Establish effective communication and collaboration among stakeholders	6
5	Incorporate into plans and schedules wildlife crossing options that can be accomplished by maintenance crews simply by retrofitting existing facilities	8
6	Continued public and agency education on wildlife and roads issues	10
7	Use standardized and vetted protocols for collecting and recording road kill carcass and wildlife-vehicle colllision data	18
8	Incorporate standardized guidelines when conducting mitigation activities	19
9	Use standardized documentation schedules to record maintenance activities in order to maintain crossings and fencing effectiveness over time	21
10	Develop and enhance agency websites to include standardized guidelines	24
11	Explicit mitigation legislation to help determine where & when mitigation is necessary, and how it is to be carried out	25

Table 5: Ranking of research priorities for transportation and wildlife in North America

Rank within Research	Priorities for Research	Rank Overall
1	Understand better the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information	2
2	Develop and summarize alternative, cost effective wildlife crossings designs and the principles they are based on	5
3	Develop wildlife crossing structure designs and guidelines for the full suite of animals in an area to help facilitate permeability for many species	7
4	Develop state-based habitat connectivity analyses for every state	9
5	Develop a standardized monitoring protocol to assess crossing effectiveness	11
6	Develop guidelines to decide when wildlife mitigation is necessary (both mandated and voluntary)	12
7	Develop standardized inventories of wildlife crossings by state for better management and maintenance of these crossings, and to better assess the need for future crossing	13
8	Increase our understanding of the effects of road density on wildlife populations	14
9	Develop prototype animal/vehicle collision safety models to predict where wildlife-vehicle colllision "hotspot" areas are and may be on future roads	15
10	Improve ecosystem valuation for use in mitigation measures, to help establish mitigation cost-effectiveness (such as monetary value of the reduction of wildlife-vehicle colllisions, or increased landscape permeability)	16
11	Standardize spatially accurate road kill carcass and wildlife-vehicle colllision data collection	17
12	Create a comprehensive synthesis document that establishes the indirect effects of roads and road density on ecosystems, and how these cumulative effects may in turn influence landscape permeability for wildlife	20
13	Develop reliable methods to estimate how often wildlife are in or near the road to help assess their potential in becoming involved in wildlife-vehicle colllisions	22
14	Understand better the genetic consequences of the roaded landscape on animal populations	23

Research priorities—All professions ranked the following top two priorities identically: to better understand the dynamics of animal use of mitigation structures, and to develop alternative, cost effective crossing designs. Planners and Natural Resource Professionals ranked the need to develop wildlife crossing structure designs and guidelines for the full suite of animals in an area third, while engineers/analysts ranked it fifth, and the need to develop guidelines to decide when wildlife mitigation is necessary as third. The fourth and fifth ranked research priorities among the different professions were not as closely ranked as the top five practice priorities (Appendix A Tables 41-43), and select priorities were ranked significantly different. Statistical analyses are being analyzed further to look for patterns rather than specific median value differences.

Priorities by Employer

Practice priorities—The top five practice priorities for all participants were identical but ordered differently. The top priority of the survey, early planning for wildlife, was rated number one by all except Federal Transportation Professionals (ranked third) and Consulting Company personnel (ranked second). The second-ranked practice priority, to combine animal-friendly mitigation methods, was ranked differently among the different types of employees. The third practice priority, to use conservation plans and connectivity analyses, was rated as the top priority by Federal Transportation Agency employees, second by Federal and State Natural Resource Agency personnel, and those working for Non-Profit groups, and third or fourth for the remaining types of employees. The fourth practice priority, to establish effective communication, was ranked as the second highest priority by those working for Federal and State Transportation agencies, and fourth or fifth for all other types of employees. The fifth overall practice priority, to incorporate wildlife crossing options that can be accomplished by maintenance crews through retrofits, was ranked either fourth or fifth among all types of employees. Further analyses of these practice priorities by employer are forthcoming in the Final Report.

Research priorities—The top five research priorities were not as tightly ranked as the practice priorities. The top four research priorities were each within the top 6 rankings of every employee class; however each class ranked them differently. For example, the overall number one priority to better understand the dynamics of animal use of mitigation structures, was ranked by every class of employee as number one, except for Consulting Company personnel who ranked this priority second and the need for cost effective crossing designs as their number one priority. There were several priorities that were ranked within the top five of specific employee groups but did not make the top five overall research priorities. University professionals (typically researchers) ranked the need to develop guidelines to decide when wildlife mitigation is necessary, fourth, as did those employed by State/Provincial Transportation agencies and those working for Consulting Companies. This priority was rated sixth for research in the overall survey. University professionals and Natural Resource Agency professionals rated the need to increase our understanding of the effects of road density on wildlife populations, fifth and fourth, respectively, while it rated eighth overall.

The priority to improve ecosystem valuation for use in mitigation measures and to help establish cost-effectiveness was rated overall as the tenth research priority, but was

highly rated by two types of employees, those working for Non-profit organizations (rated second), and Federal Transportation Agency professionals (rated fifth). A final analysis of the differences among employee classes will be forthcoming.

Interpretation, Appraisal, and Applications

There was a consistent trend in the results for participants, regardless of geography, profession, or employer type, to rank the same five *practice* priorities in their top five. The one exception was the fourth rank 36 Canadians gave to the need for the use of standardized and vetted protocols for collecting and recording road kill carcass and a-v-c data. Other Canadian differences may be due in part to the fact that the majority of Canada still has its full suite of large animals. With such a diversity of wildlife, the risks to drivers from collisions with both ungulates and predators are much greater than the typical animal collisions in the United States. However, because of the low number of Canadian participants, we cannot extrapolate the importance of this priority to Canada, but believe it may represent a trend worth mentioning.

These results provide clear guidance to help governments, agencies, organizations, universities, companies, and individuals focus their efforts in developing the future state of practice. Fundamental parameters will include; early incorporation of wildlife needs into the planning processes, a combination of animal-friendly mitigation methods rather than just fences, conservation plans and connectivity analyses to inform transportation planning and design processes, effective communication among stakeholders, and incorporation of plans and schedules for wildlife crossing options that can be accomplished by maintenance crews by simple retrofit of existing facilities.

In ranking the *research* priorities, the different categories of participants exhibited more widely varied values than in their ranking of practice priorities. The top ranked research priority to better understand the dynamics of animal use of mitigation structures was the top research priority for all categories of nation of origin, profession, and employees except for those working for consulting firms who ranked it second. The second overall research priority to develop cost effective wildlife crossing designs ranked first among those working for Consulting Companies, and third among Canadians, State and Federal Natural Resource Agency personnel and University personnel. Those working for Non-profit Organizations gave it a lower value of sixth. The third research priority to develop wildlife crossing structure designs and guidelines for the full suite of animals received a variety of rankings from the different categories of participants, but was consistently in the top five priorities for all categories of participants. The fourth overall research priority to develop state-based habitat connectivity analyses was ranked within the top six priorities by all classifications of participants, except by those from Canada (eleventh), engineers (tenth), and planners (eighth). The fifth research priority to develop a standardized monitoring protocol to assess crossing effectiveness was ranked within the top six priorities by residents of both U.S. and Canada, all professions, and all employees of State and Federal Agencies. Every one of the top five research priorities was a top-five research priority for all the professions with the exception of the need to develop state-based habitat connectivity analyses, which the planners and engineers did not value as highly as natural resource professionals. Further analyses and statistical scrutiny of the ranking of these priorities may reveal other trends.

The results of the ranking of research priorities show the overall high support for the top three priorities: to better understand the dynamics of animal use of mitigation structures, to develop cost effective wildlife crossings designs, and to develop wildlife crossing structure designs and guidelines for the full suite of animals. These and other research priorities can help form a clearer picture of the areas in need of highest research attention. They also demonstrate a need to better communicate the results of these research efforts.

Statistical differences among professions' median ranking of priorities were significant for select priorities, but may be due in part to the tendency of some professions, such as engineering, to systematically use lower values for overall ranking while other professions systematically use higher numbers to rank priorities, which was the tendency of Planners and Natural Resource Professionals. Statistical differences among median values of how each priority was ranked among the different categories of participants have not been inserted at this stage of analysis, but will be included in the final report.

Priority rankings were also heavily influenced by the discrepancy in number of participants from certain categories. Although efforts were made to include as many engineers and Canadians as possible, their numbers remained lower than natural resource professionals and Americans, respectively. The rankings were also influenced heavily by the high numbers of transportation professionals working for state and provincial DOT/MoTs. This is in direct accordance with the job responsibilities of this group, and they are the most appropriate employees for this continental survey. This group had the most representation in the survey (n = 181), and as such, this employer group was the most influential in ranking priorities. For example in the research priorities, the need for alternative cost effective designs was ranked as first or second by only three employee types, yet it was rated overall as second research priority, in part because of the large number of participants in the state/provincial and federal employee categories who overall rated it as the second highest research priority. The differences among different categories of respondents were in part accounted for when we separated out priority rankings by nation, profession, and employer, so readers could view the priorities from these different perspectives. The Games-Howell post hoc test was also used in analyzing statistical differences among groups of unequal size. Future analyses will continue to delve into these differences and similarities among the categories of participants.

Conclusions and Suggested Research

We have identified the top 25 priorities for research and practice in the field of transportation and wildlife for North America. The results show a clear consensus among all participants on the top five *practice* priorities:

1) Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process

2) Combine several animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than relying on just one method

3) Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out

4) Establish effective communication and collaboration among stakeholders

5) Incorporate wildlife crossing options into plans and schedules that can be, accomplished by maintenance crews by simple retrofit of existing facilities

These statements call for a plan of action. In Appendix A we describe the background and the next steps for these and all priorities.

Priorities for research presented a greater challenge for consensus of opinion and were not as consistently rated by survey participants. In general, the top three research priorities were among the top five research priorities by all categories of participants. In general, the top three most consistently highly rated research priorities for North America are:

1) To better understand the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information

2) To develop and summarize cost effective wildlife crossing designs and the principles they are based on

3) To develop wildlife crossing structure designs and guidelines for the full suite of animals in an area to help facilitate permeability for many species

These priority statements lead to the next step, which is to describe what is known, and how we build upon that knowledge. Within Appendix A is a call to action. We hope this consensus on top priorities for research and practice will help to facilitate actions across North America to address mitigation and research needs to help create a roaded landscape that is more permeable for wildlife and safer for motorists. For example, the top five priorities can lead agency personnel in directing early planning for wildlife in transportation planning, help encourage the installation of suites of mitigation measures for wildlife, promote the use of connectivity analyses in transportation planning, and the development and use of alternative cost-effective crossing designs. Researchers can see the need to design studies that address our need to better understand the dynamics of animal use of mitigation structures, and disseminate this information. Additional priorities can help raise awareness for the need for better communication among agency personnel and the public, and help states to initiate standardized guidelines and methodologies involved in wildlife crossings and animal-vehicle collisions. Organizations working at the national level may use these guidelines to help direct policy initiatives as well.

CHAPTER 3: PHASE II SEGMENTS

SAFETY DATA ANALYSIS ASPECTS (3.1)

Lead:
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Abstract

This report documents safety research that involved analyses of Wildlife vehicle collisions (WVCs) and road environment data from State Department of Transportation (DOT) sources. The results would help in the development of guidelines on:

1) Methods for identifying WVC problem locations

2) Evaluating the safety effectiveness of crossing mitigation measures

3) The establishment of a monitoring program to facilitate the identification of crash prone locations and the evaluation of crossing mitigation measures

4) Cost-benefit and cost-effectiveness considerations

It is expected that these guidelines will be key ingredients of the decision making toolkit to be developed as part of this project for use by DOTs in safety management related to WVCs. There were two fundamental aspects to the research: 1) The application of reported WVC data typically available in state DOT databases, and 2) An investigation of how the application of two databases, reported WVCs and carcass removals, can lead to different roadway improvement decisions.

For the first aspect, safety performance functions (SPF) were calibrated for four states. These functions relate police reported WVCs to traffic volume and road environment data usually available in DOT databases. Three SPF applications most relevant to the development of the desired guidelines are illustrated. These are:

1) Network screening to identify roadway segments that may be good candidates for wildlife-vehicle colllision countermeasures

2) The evaluation of the effectiveness of implemented countermeasures

3) Estimating the effectiveness of potential countermeasures

For the second aspect, a series of activities were completed to evaluate the hypothesis that the magnitude and patterns of reported WVC and deer carcass removal data as they typically exist at a DOT were different. These two types of data have been used in the past, but their differences could lead to varying and possibly ineffective/inefficient WVC-related policy and countermeasure decision-making. Reported WVCs and deer carcass removal locations were acquired from Iowa, and plotted within a Geographic Information System (GIS) platform. These plots were visually compared at statewide and example road corridor levels. The challenges of combining these two databases in the same GIS platform are discussed in this report. The spatial patterns of the two types of data were clearly different, and their calculated safety

measures (e.g., average frequencies) varied. Negative binomial models or SPFs were also created for both the reported WVC and deer carcass removal data. The models for these two types of data, which theoretically describe the same problem, had different coefficients and/or input variables. The use of the GIS plots, safety measures, or predictive models developed as part of this project could, therefore, lead to different WVC-related polices and countermeasure implementation and evaluation decisions. The choice of the database used to define and evaluate the WVC problem and its potential countermeasures should be considered carefully. Recommendations are provided in this report about how the databases might be used appropriately and how the data should be collected.

Introduction

This research segment covers the work done in the safety data analysis aspects of the project. Throughout this report the authors interchange the use of the words 'collision' and 'crash.' They are meant to convey the same phenomena.

The broad objectives of this project required, among other tasks, the conduct of safety research that involved an analysis of WVCs and road environment data from State Department of Transportation (DOT) sources. Specifically, the planned purpose of the safety analysis was to try to produce results that would feed into Task 7 to assist with the development of guidelines on:

1) Methods for identifying wildlife-vehicle colllision problem locations

2) Evaluating the safety effectiveness of crossing mitigation measures

3) The establishment of a monitoring program to facilitate the identification of crash prone locations and the evaluation of crossing mitigation measures

4) Cost-benefit and cost-effectiveness considerations

It is expected that these guidelines would be key ingredients of the decision making toolkit to be developed as part of this project for use by DOTs in safety management related to WVCs. The sections that follow document our efforts towards developing these guidelines. There are two aspects to the safety research that, although linked, are summarized separately.

Aspect 1: The application of reported WVC data typically available in state DOT databases

Aspect 2: An investigation of how the application of two databases, reported WVCs and carcass removals, can lead to different roadway improvement decisions

Aspect 1: Application of reported wildlife vehicle collision data

The general objectives of the research undertaken for this aspect are quite consistent with those of *SafetyAnalyst* (www.safetyanalyst.org), a safety management tool being developed by Federal Highway Administration (FHWA) for use by DOTs.

According to that website: "SafetyAnalyst is envisioned as a set of software tools used by state and local highway agencies for highway safety management. SafetyAnalyst

will be used by highway agencies to improve their programming of site-specific highway safety improvements. SafetyAnalyst will incorporate state-of-the-art safety management approaches into computerized analytical tools for guiding the decision-making process to identify safety improvement needs and develop a systemwide program of site-specific improvement projects. SafetyAnalyst will have a strong basis in cost-effectiveness analysis; thus, SafetyAnalyst will have an important role in ensuring that highway agencies get the greatest possible safety benefit from each dollar spent in the name of safety."

These tools and the general objectives of this research address three general aims:

1) Identify crash prone locations for existing or proposed roads for all crash types combined or for specific target crash types

2) Aid in the evaluation, selection and prioritization of potential mitigation measures

3) Evaluate the effectiveness of mitigation measures already implemented

Meeting these objectives requires the use of state of the art methods (such as predictive negative binomial models and empirical Bayes procedures) to produce a widely accepted and useable tool that could be readily applied by DOTs in their completion of items 1 and 2 for animal–vehicle collisions, and to provide initial insights as part of a framework for future research to make additional progress on item 3 with respect to wildlife crossings. It is expected that results of this research project, specifically the predictive models developed, can be applied within *Safety Analyst* in undertaking tasks 1, 2, and 3 above with respect to animal–vehicle collisions.

Aspect 2: Comparison of wildlife-vehicle colllision and carcass removal data

It has been shown that reported WVC data may represent only a small portion of the large number of WVCs that occur.[61,201] A second type of data – from records of carcass removals – could be used to better describe the WVC problem. This aspect of NCHRP 25-27 was completed to investigate the hypothesis that roadside carcass removal data cannot only describe the magnitude of the animal collision problem, but may also follow different spatial patterns than WVC data. The choice of the database (crashes or carcasses) used to evaluate the WVC problem, therefore, may lead to the identification of different 'hot spot' locations and ultimately different countermeasure improvements. This hypothesis is tested visually (through GIS plots), in a general manner through basic statewide quantitative measures, and through the development of comparable negative binomial WVC and deer carcass removal models. WVC and deer carcass removal data, by roadway location, were obtained from the Iowa Department of Transportation (IaDOT).

The creation of GIS-based data that included the attributes and location of roadway segment cross sections, reported WVCs, and deer carcass removals can be used to answer a number of questions. Some of these questions include:

1) How many more deer carcass removals than reported WVCs occur statewide and along individual roadway segments?

2) Are different 'high crash' segments identified when reported WVCs and deer carcass removal data are used for the safety analysis of individual roadway segments? In other words, do they have different occurrence patterns?

3) Are there any apparent relationships between roadway cross section characteristics and reported WVCs? Are these relationships, if any, similar for deer carcass removal data?

Research Approach: Methods and Data

The research approach emerged from a review of the existing literature as it pertains to the objectives for this part of the research, specifically from a consideration of the gaps in existing knowledge that could be addressed as part of this project. As before, the two complementary aspects are addressed separately.

Methods

Aspect 1: Application of reported animal–vehicle collision data—Predictive models for animal–vehicle crashes (also called safety performance functions) are crucial to state of the art methods for filling safety analysis gaps and developing the requisite guidelines for mitigating these collisions. These models are derived from historical data to relate collision frequency to physical roadway and roadside characteristics and to measures of exposure. They were developed for, and apply to, reported large wildlife-vehicle crashes (as distinguished from data reported only as carcass pick-up) and, with a view to the application of the models, for use only with those variables for which data are readily available within the typical DOT safety databases. Since animal exposure data (a measure of the numbers of animals involved in WVC that are near the road, and the amount of time they spend near the road over the course of a specific measured time unit) are not among these readily available variables, this approach will result in some unexplained variation in the dependent variable. This approach further limits the safety model inputs to roadway (between shoulder edges) variables since few DOT databases include roadside information (e.g., guardrail, roadside sight distance), or adjacent landscape (off right-of-way) characteristics. Even so, it is still necessary to estimate models for lower levels of data availability that may exist in some jurisdictions. The result is three fundamental levels of models.

Level 1: These models include only the length and annual average daily traffic volume (AADT) of a segment

Level 2: These models require that segments be classified as flat, rolling or mountainous terrain, and also use the length and AADT of a segment

Level 3: These include, in addition to the Level 2 variables, additional roadway variables such as average lane width

The SPFs can be used in a number of applications:

<u>Application A:</u> They can be used with the cautions noted in the six month interim report to identify roadway factors associated with a high propensity for animal–vehicle collisions. These cautions pertain to possibly counterintuitive inferences that may result from omitted, incorrectly specified or correlated factors. This application can be useful in roadway design and planning decisions that have implications for animal–vehicle collisions.

<u>Application B:</u> They can be used in the identification of roadway segments that may be good candidates for animal–vehicle collision countermeasures.

<u>Application C:</u> They can be used in estimating the effectiveness of potential countermeasures that are considered for candidate segments.

<u>Application D:</u> They can be used in the evaluation on the effectiveness of implemented countermeasures using state of the art methods for observational before-after studies.[114]

For the last three applications, which are key in this project, crash history often is used as a predictor. However, it is now well recognized as a poor predictor since it tends to be short-term (< 3 years) rather than long term (≥ 3 years) and therefore subject to random fluctuation and associated vagaries of regression to the mean. The result is that for Application A, resources are often wasted on safer sites that are wrongly identified and good candidates may be ignored. This can result in an exaggeration of the countermeasure effectiveness estimates for Applications C & D. The regression to the mean problem cannot be overemphasized and so is illustrated in Appendix D.

While the SPF can provide less biased predictions than the crash count for Applications B, C, and D, estimates obtained from these models can have a high variance because of the inability to include potentially important explanatory variables in them. In recognition of this difficulty and the problems with estimates from crash counts, an empirical Bayes (EB) procedure has been used in state of the art applications. This procedure in essence takes a weighted average of the two estimates, recognizing that both provide important clues as to a location's safety. In effect, by using the collision count to refine the SPF prediction, the EB procedure accounts for factors, such as off right-of-way characteristics and animal exposure, which affect wildlife-vehicle colllision frequency but are not in the model. For example, a location which has more animal movements than the 'average' location, but which is similar in the characteristics of the prediction model, will tend to have more collisions than the 'average' location. With consideration being given to the EB refinement, it will also have a higher crash prediction. The EB procedure is illustrated by way of example applications, in the section on Interpretation, Appraisals, and Applications.

The development of the SPFs are involved in determining which explanatory variables should be used, whether and how variables should be grouped, and how variables should enter into the model (i.e., the best model form). Consistent with the common research practice in developing these models, generalized linear modeling was used to estimate model coefficients, assuming a negative binomial error distribution. In specifying a negative binomial error structure, the dispersion parameter, k, which relates the mean and variance of the regression estimate, is estimated from the model and the data. The value of k is such that the smaller its value the better a model is for the set of data (See Appendix B). Conveniently, the dispersion parameter estimated in the SPF

calibration is used to derive the weights for the two sets of information used in the EB procedure.

Aspect 2: Comparison of wildlife-vehicle colllision and carcass removal data—The tasks completed for this research were done to evaluate the value of collecting and plotting WVC and deer carcass removal data by location, and to test the hypothesis that these two datasets may also identify *different roadway locations* for potential WVC countermeasures. The magnitude and patterns of location-based WVC reports and deer carcass removal datasets in Iowa were compared qualitatively through visual GIS plots and quantitatively (e.g., frequency per mile). The GIS plots and summary tables from these comparison activities are summarized in The Findings section of this safety data analysis report. For Aspect 1 (Application of reported wildlife-vehicle colllision data), negative binomial modeling was used. WVC and deer carcass removal prediction models (or SPFs) that include traffic flow and roadway cross section elements as potential input variables, were created and compared. The results of these activities are described in the Findings section.

Several types of computer software were used to overlay, present, and summarize the WVC and deer carcass removal data within the GIS platform. Microsoft Excel™ and TrueBasic™ were used to manipulate the deer carcass removal data. The ArcGIS 9.1™ platform, was used to spatially present and analyze the crash and carcass datasets. ArcCatalog™ was used as a file management program and applied specifically for organizing spatial data. Most of the mapping activities took place in ArcMap™. ArcToolbox™ was used for some of the more complicated spatial analysis, and the large size of the roadway inventory database files required the use of FileMaker™. The modeling of the WVC and deer carcass removal information was completed with the statistical software SAS™.

Data

Aspect 1: Application of reported animal–vehicle collision data— The models for predicting the frequency of reported wildlife-vehicle crashes were developed for rural two-lane, rural multilane and rural freeway roadways using Highway Safety Information System (HSIS) data from California, North Carolina, Utah, and Washington. These are the typical classifications used by DOTs in other aspects of safety management. Table 6 through Table 9 summarize the data used.

Table 6: Data summary for rural two-lane roadways

State	Data period	Length (mi.)				AADT			Total Crashes	Crashes/mile-year		
		Total	mean	min	max	mean	min	max		mean	min	max
CA	1991-2002	8,349	0.644	0.001	26.137	4893	63	37041	5,378	0.068	0.000	16.670
NC	1990-2001	25,165	1.322	0.010	18.980	2466	2	80428	59,280	0.140	0.000	8.330
UT	1985-2000	9,260	2.503	0.010	40.380	1541	1	17424	15,334	0.186	0.000	6.250
WA	1993-1996	5,362	0.601	0.010	28.660	4334	87	23917	1,746	0.078	0.000	12.500

Table 7: Data summary for rural multi-lane roadways

State	Data Period	Length (mi.)				AADT			Total Crashes	Crashes/mile-year		
		Total	Mean	min	max	mean	min	max		mean	min	max
CA	1991-2002	994	0.359	0.003	7.689	14312	304	78300	1,205	0.116	0.000	4.900
NC	1990-2001	1,185	0.803	0.010	9.440	11134	100	63332	5,406	0.347	0.000	8.330
UT	1985-2000	291	0.599	0.010	4.840	6162	186	61393	4,021	0.654	0.000	6.430
WA	1993-1996	322	0.423	0.010	63.440	12588	172	54274	251	0.218	0.000	12.500

Table 8: Data summary for rural freeways

State	Years of Data	Length (mi.)				AADT			Total Crashes	Crashes/mile-year		
		Total	Mean	min	max	Mean	Min	max		mean	min	max
CA	1991-2002	1,659	0.536	0.001	14.917	22520	3275	86700	1,326	0.089	0.000	9.260
UT	1985-2000	700	1.928	0.010	13.730	10579	2776	64402	5,145	0.608	0.000	7.290
WA	1993-1996	400	0.685	0.010	8.320	18179	4124	49952	257	0.194	0.000	25.000

Table 9: Variables available for modeling

State	Roadway Variables	State	Roadway Variables
CA	AADT Design Speed in mph Divided/Undivided Lane width in feet Shoulder Width in feet Median Barrier Type Median Width in feet Number of Lanes Surface Type Surface Width in feet Terrain (level, rolling, mountainous)	UT	AADT Average Degree of Curvature Design Speed in mph Lane width in feet Median Type Median Width in feet Number of Lanes Paved Roadway Width in feet Percentage Truck Traffic Shoulder Type Speed Limit in mph Terrain (level, rolling, mountainous)
NC	AADT Shoulder Type Shoulder Width in feet Median Type Median Width in feet Number of Lanes Speed Limit in mph Surface Width in feet Terrain (level, rolling, mountainous)	WA	AADT Average Degree of Curvature Shoulder Width in feet Shoulder Type Median Barrier Type Median Width in feet Median Type Number of Lanes Speed Limit in mph Surface Width in feet Terrain (level, rolling, mountainous)

Aspect 2: Comparison of wildlife-vehicle colllision and carcass removal data— Three different databases were used to compare the magnitude and patterns of WVCs and deer carcass removals in Iowa. First, police-reported WVC information in a GIS acceptable format were acquired from the IaDOT. Ten years of WVC report data was provided for the entire state of Iowa. These data included the location of the WVCs and information provided on the police reports (e.g., severity, surface conditions, time of day, and age of driver). It is believed that the great majority of these reported WVCs involved white-tailed deer. The reported WVCs in 2001, 2002, and 2003 were used in this analysis. The WVC locations were provided by latitude and longitude coordinates. These WVCs were plotted on a roadway map of Iowa within a GIS platform (See Figure 4).

The two other datasets that were used included information about deer carcass removals and roadway cross sections. The locations of the deer carcass removals by IaDOT personnel were plotted to the nearest mile marker. The gender of the deer removed was also noted if possible. Annual average daily volume estimates and cross section information (e.g., surface width, median type, and shoulder width) for each roadway segment within Iowa were also used.

WVC and deer carcass removal data were plotted in a GIS platform. Figure 4 is an example of the data from 2002. These data were compared visually and quantitatively on a statewide and example corridor basis. Table 10 shows the number and percent of Iowa roadway mileage, reported WVCs, and deer carcass removals along roadways with varying characteristics.

Traffic volume and cross section attribute data collected were used to develop WVC and deer carcass removal prediction models. Descriptive statistics for the 2001 to 2003 roadway length, average annual daily traffic, WVC, and deer carcass removal data used in the model development are summarized in Table 11. The length of the segments evaluated was primarily defined by the changes in roadway cross section design (e.g., number of lanes). Only those rural roadway segments with a length of 0.1 mile were used in the model development.

a.
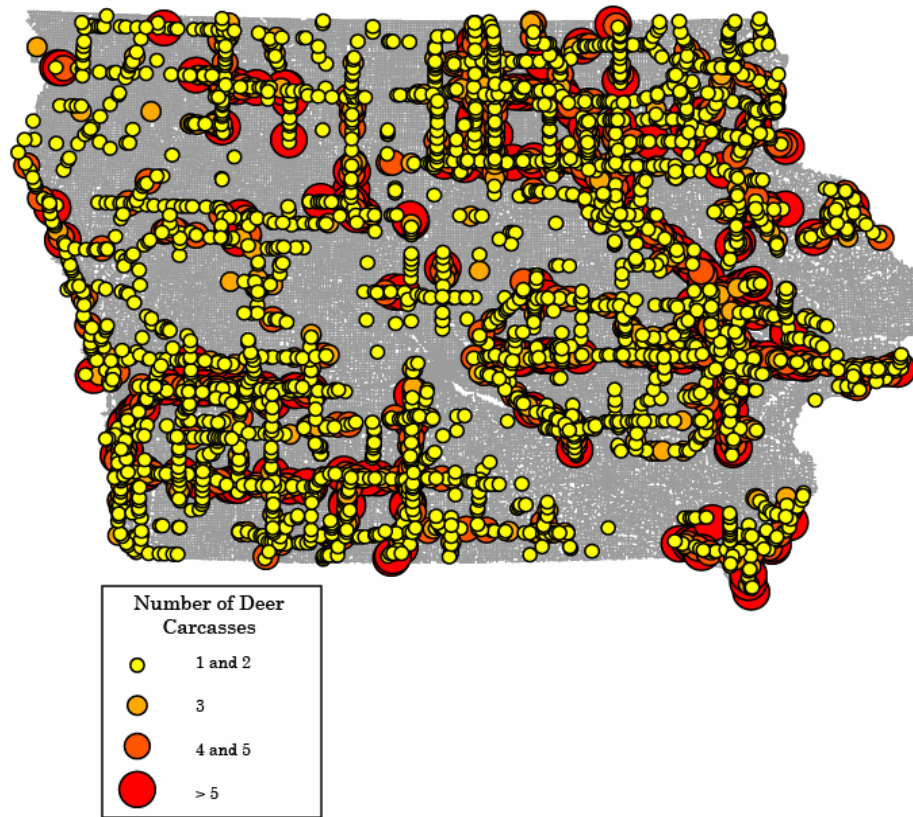
b
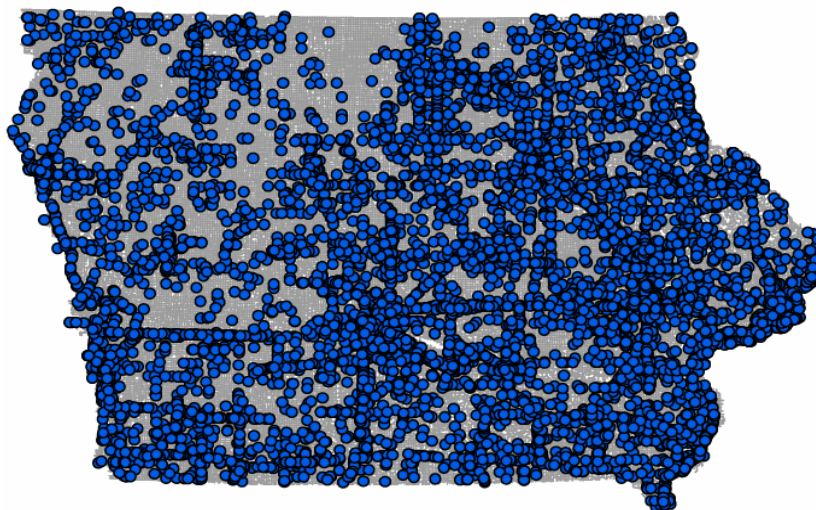
Figure 4: Deer carcass removal (top) and WVC locations (bottom) in Iowa, 2002

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Table 10: Total wildlife-vehicle crash and deer carcass removals by roadway characteristic (2001-2003)

	Number and Percent of Roadway Miles[1]	Number and Percent of Wildlife-vehicle Crashes	Number and Percent of Deer Carcass Removals
Roadway System			
Interstate	1,020.46 (0.9%)	1,892 (8.2%)	6,382 (25.3%)
U.S. Route	3,635.25 (3.2%)	6,042 (26.2%)	10,205 (40.4%)
Iowa State Route	5,039.19 (4.4%)	5,722 (24.8%)	8,075 (32.0%)
Farm to Market Route	30,843.84 (27.3%)	6,826 (29.6%)	119 (0.4%)
Area Type			
Rural	97,885.5 (86.6%)	20,222 (87.6%)	22,155 (87.7%)
Urban	15,172.75 (13.4%)	2,872 (12.4%)	3,103 (12.3%)
Number of Lanes[2]			
Two	109,471.10 (96.8%)	16,429 (71.1%)	13,393 (53.0%)
Four	2,033.43 (1.8%)	4,898 (21.2%)	9,650 (38.2%)

[1]Roadway mileage changes each year. Number and percentage of roadway miles in table represents average annual mileage that existed from 2001 to 2003

[2]Number includes through, turn, and two-way left-turn lanes

Table 11: Modeling database summary (rural segments ≥ 0.1 mile)

Roadway Category	Two-Lane Rural Roadway				Multi-Lane Rural Roadway			
	Total	Mean	Min.	Max.	Total	Mean	Min.	Max.
Length (Miles)	6,477.01	0.49	0.10	1.77	1,270.86	0.35	0.10	1.39
Average Annual Daily Traffic (AADT)	NA[1]	2,431	20	13,000	NA[1]	12,904	180	77,433
Wildlife-vehicle Crashes/Mile-Year	6,721 Crashes	0.40	0.00	16.67	3,397 Crashes	0.91	0.00	14.58
Carcass Removals/Mile-Year	11,644 Carcasses	0.65	0.00	79.17	8,174 Carcasses	2.03	0.00	93.33

[1]NA = Not Applicable

Findings and Results

Aspect 1: Application of reported wildlife vehicle collision data

Table 12 throughTable 14 provide details of the SPFs. For each of the four states, three levels of SPFs were developed with varying data requirements. The first level requires only the length and AADT of a segment. The second level also requires segments to be classified as flat, rolling, or mountainous terrain. The third level SPFs include additional roadway variables such as average lane width. Segments are defined as sections of roads, generally between significant intersections and having essentially common geometric characteristics. Illustration of the application of the SPFs developed is a key component of this aspect of the safety research. These applications are illustrated in the Interpretation, Appraisals and Applications Section.

In general, the calibrated SPFs make good intuitive sense in that the sign, and to some extent the magnitude, of the estimated coefficients and exponents accord with expectations. Surprisingly the exponent of the AADT term, though reasonably consistent for the three levels of models in a state, varies considerably across states. This exponent, as expected, varies significantly across facility types, reflecting differences in traffic operating conditions. The variables found to be significant are as follows:

AADT: Annual average daily traffic
SURFWID: Total surface width (feet)
LANEWID: Average lane width (feet)
HI: Average degree of curvature
SPEED: Posted speed in North Carolina (mph); Design speed in California (mph)
MEDWID: Median width (feet)
MEDTYPE: Positive barrier or unprotected

For application in another state, or even for application in the same four states for different years to those in the calibration data, the models should be recalibrated to reflect differences across time and space in factors such as collision reporting practices, weather, driver demographics, and wildlife movements. In essence, a multiplier is estimated to reflect these differences by first using the models to predict the number of collisions for a sample of sites for the new state or time period. The sum of the collisions for those sites is divided by the sum of the model predictions to derive the multiplier. Further details of this procedure are provided in Appendix B.

In deciding which of the four models is best to adopt for another state it is necessary to conduct goodness of fit tests. Choosing the most appropriate model is especially important because the exponents for AADT, by far the most dominant variable, differ so much between states. A discussion of these tests is provided in a recent FHWA report.[240] A summary is presented as part of Appendix B.

Aspect 2: Comparison of wildlife-vehicle colllision and carcass removal data

The findings from this aspect of the safety analysis focused on the challenges related to combining WVC and deer carcass removal data on a roadway network within a GIS platform. This information is useful because it helps define where the WVC and deer

carcass removal data were reported or collected, and whether the occurrence of either is actually over- or under-represented along roadways with particular characteristics. In addition, the results of visual and quantitative WVC, and deer carcass removal comparisons (statewide, example corridor, and model content) are described.

In general, the amount of two-lane roadway mileage used in the modeling was more than five times greater than the multi-lane roadway mileage. Two-lane roadways with medians were not included. The multi-lane database included any State Route, U.S. Route, or Interstate with more than two through lanes. Overall, despite the proportions of roadway mileage in the database, only about 1.7 WVCs were reported along the two-lane roadways for every one WVC reported along the multi-lane roadways. Similarly, the number of deer carcasses removed from two-lane roadways was about 1.4 times that removed from the multi-lane roadways. The mean number of WVCs and carcass removals per mile-year, however, along the multi-lane roadways in the database are much greater than those along the two-lane roadways. Of course, the average annual daily traffic along the multi-lane rural roadways was also greater than the traffic flow using the two-lane roadways.

WVC and carcass removal GIS activities—There are a number of advantages to incorporating information into a GIS platform. These advantages include an increased ability to organize and integrate spatial data, the relatively easy presentation of the data, and the capability to quickly analyze and/or compare one or more datasets. Visual patterns in the data are also easier to discern and data can be assembled from multiple sources and formats to produce broader and more rigorous evaluation activities. The GIS process in a safety data project is typically composed of three steps: 1) data acquisition and importation, 2) data management, and 3) spatial analysis. The first steps are often the most difficult.

The general objective of the GIS activities in this aspect of the safety data analysis was simply to combine and document spatial representations of the WVC and deer carcass removal locations. Deer carcass removal data and locations are not normally available in any consistent manner. Plots of WVC and deer carcass removal locations in Iowa for 2002 are shown in Figure 4. The WVC data were relatively easy to incorporate into the GIS platform because latitude and longitude coordinate positions for each incident were available. The carcass removal locations, on the other hand, were estimated to the nearest 0.1 milepost, and were not as easily imported and layered. Not surprisingly, the accuracy of the estimated deer carcass removal locations was not the same as that available for the WVCs (during the 2001 to 2003 analysis period considered). In addition, the individual whole milepost locations (e.g., 1.0, 2.0, etc.) on the Iowa roadway GIS map were the only spatial data connection that would allow the plotting of the deer carcass removal locations. For schedule and budget reasons, therefore, the estimated locations of the deer carcass removals were rounded to the nearest milepost, summed, and plotted. The total number of deer carcass removals in 2002 is plotted in Figure 4 at each milepost (with scaled and color circles to represent the different number at each location). This spatial modification was considered appropriate given the accuracy of the datasets provided and those likely to be available from other states. The impact of this

Table 12: SPFs for rural two-lane roadways

State/Model	Terrain	Model Form: Total wildlife-vehicle crashes/mile-yr $= \alpha(AADT)^{\beta_1} \exp(\beta_2 SURFWID + \beta_3 HI + \beta_4 SPEED + \beta_5 LANEWID)$						
		$\ln(\alpha)$ (s.e.)	β_1 (s.e.)	β_2 (s.e.)	β_3 (s.e.)	β_4 (s.e.)	β_5 (s.e.)	Dispersion parameter
CA 1	All	-7.8290 (0.1868)	0.6123 (0.225)					1.6098
CA 2	Flat	-8.7034 (0.2005)	0.6636 (0.0228)					1.4831
	Rolling	-8.1810 (0.1930)						
	Mountainous	-8.0343 (0.1989)						
CA 3	Flat	-8.5357 (0.2046)	0.6518 (0.0230)			Design ≤ 55 -0.3310 (0.0449) Else = 0		1.4493
	Rolling	-7.9275 (0.1968)						
	Mountainous	-7.7157 (0.2029)						
NC 1	All	-4.5625 (0.0576)	0.3743 (0.0078)					0.9222
NC 2	Flat	-4.3984 (0.0745)	0.3637 (0.0077)					0.8142
	Rolling							
	Mountainous	-5.5363 (0.0653)						
NC 3	Flat	-4.3805 (0.0773)	0.4447 (0.0087)	-0.0122 (0.0022)		Posted < 55 -0.7165 (0.0248) Else = 0		0.7353
	Rolling							
	Mountainous	-5.7195 (0.0685)						
UT 1	All	-9.1135 (0.1423)	1.0237 (0.0205)					1.7610
UT 2	Flat	-9.3123 (0.3385)	1.0092 (0.0410)					1.6123
	Rolling	-9.0528 (0.3393)						
	Mountainous	-8.7728 (0.3006)						
UT 3	Flat	-12.987 (0.9608)	0.8073 (0.0455)			Posted ≤ 55 -0.6646 (0.1344) Else = 0	0.4751 (0.0838)	1.3985
	Rolling	-12.803 (0.9613)						
	Mountainous	-12.408 (0.9485)						
WA 1	All	-8.6850 (0.3020)	0.7802 (0.0367)					1.3825
WA 2	All	-8.5319 (0.3552)	0.8034 (0.0426)		-0.0584 (0.0117)			1.0237
WA 3	All	-8.5161 (0.3493)	0.7622 (0.0426)		-0.0696 (0.0124)	Posted ≤ 55 0.4358 (0.0964) Else = 0		0.9528

Table 13: SPFs for rural multi-lane roadways

State/Model	Terrain	Model Form: Total wildlife-vehicle crashes/mile-yr $= \alpha\left(AADT\right)^{\beta_1} \exp\left(\beta_2 MEDWID + \beta_3 HI + \beta_4 SPEED\right)$			
		$\ln(\alpha)$ (s.e.)	β_1 (s.e.)	β_2 (s.e.)	β_3 (s.e.)
CA 1	All	-5.2576 (0.4397)	0.3290 (0.0470)		
CA 2	Flat	-6.4592 (0.4523)	0.3926 (0.0464)		
	Rolling	-5.7615 (0.4398)			
	Mountainous	-5.5220 (0.4498)			
CA 3	Flat	-6.4885 (0.4485)	0.4145 (0.0464)	-0.0057 (0.0015)	
	Rolling	-5.8372 (0.4360)			
	Mountainous	-5.6577 (0.4462)			
NC 1	All	-3.3660 (0.6314)	0.2501 (0.0684)		
NC 2	Flat	-2.5310 (0.6063)	0.1736 (0.0641)		
	Rolling				
	Mountainous	-4.1844 (0.5934)			
NC 3	Flat	-2.4303 (0.5871)	0.1858 (0.0621)		
	Rolling				
	Mountainous	-4.0785 (0.5741)			
UT 1	All	-4.1217 (0.6231)	0.4414 (0.0742)		
UT 2	Flat	-4.4878 (1.5295)	0.3900 (0.1754)		
	Rolling	-3.4508 (1.5013)			
	Mountainous				
WA 1	All	-12.7417 (1.9219)	1.2066 (0.2028)		
WA 2	Flat	-12.9945 (1.9091)	1.1398 (0.1987)		
	Rolling	-11.8326 (1.8894)			
	Mountainous				
WA 3	Flat	-14.1608 (2.1029)	1.2721 (0.2153)		0.1244 (0.0775)
	Rolling	-13.2591 (2.0800)			
	Mountainous				

Table 14: SPFs for rural freeways

State/Model	Terrain	Model Form: Total wildlife-vehicle crashes/mile-yr $= \alpha(AADT)^{\beta_1}\exp(\beta_2 MEDWID + \beta_3 HI + \beta_4 SURFWID + \beta_5 MEDTYPE)$						
		$\ln(\alpha)$ (s.e.)	β_1 (s.e.)	β_2 (s.e.)	β_3 (s.e.)	β_4 (s.e.)	β_5 (s.e.)	Dispersion parameter
CA 1	Flat	-6.2814 (0.7166)	0.2810 (0.0726)					1.5885
	Rolling	-4.7526 (0.7098)						
	Mountainous							
CA 2	Flat	-5.6746 (0.6925)	0.3050 (0.0700)	-0.0126 (0.0014)				1.3543
	Rolling	-4.3198 (0.6857)						
	Mountainous							
UT 1	All	-4.3930 (1.4121)	0.4356 (0.1550)					1.9966
UT 2	Flat	-7.8707 (1.4831)	0.7272 (0.1632)					1.5641
	Rolling	-6.9760 (1.4811)						
	Mountainous	-6.0374 (1.4516)						
UT 3	Flat	8.0592 (1.4808)	0.7472 (0.1630)				Median Type Positive barrier -1.0633 (0.4623) Unprotected 0.0000	1.5277
	Rolling	-7.1234 (1.4773)						
	Mountainous	-6.0651 (1.4465)						
WA 1	All	-15.5153 (1.7866)	1.3969 (0.1809)					0.8816
WA 2	Flat	-16.8612 (1.7977)	1.4355 (0.1784)					0.7807
	Rolling	-15.8572 (1.7634)						
	Mountainous	-15.4443 (1.7846)						
WA 3	Flat	-9.9014 (3.9034)	1.4507 (0.1793)			-0.1483 (0.0765)		0.7867
	Rolling	-8.8909 (3.8877)						
	Mountainous	-8.4610 (3.8975)						

spatial alteration on the results of the comparisons and modeling activities in this research are noted where appropriate.The statistics in Table 10 might also be used for gross comparison purposes to roadway segments of interest with similar characteristics. A review of the percentages by roadway system reveals that the deer carcass removal data are primarily from the interstates and U.S. or state roadways. This trend is not surprising because the data provided was from IaDOT. About 80% of the WVC reported, on the other hand, occurred on U.S. or state routes and farm to market roadways. The percentage of WVCs and carcasses removed along Interstate, U.S. Routes, and State Routes are much greater than their statewide roadway mileage. For every reported WVC along the interstate there were more than three carcasses collected. Table 10 does show, however, that the percentage of urban and rural roadway mileage is essentially the same as the percentage of WVCs and deer carcass removals in these areas. From a roadway mileage point of view, the number of WVCs and deer carcass removals also appear to be over-represented along four-lane roadways. More than 90% of the WVCs and deer carcass removals from 2001 to 2003 occurred along two- and four-lane roadways.

Statewide and sample corridor comparisons—The availability of WVC and deer carcass removal data in Iowa within a GIS platform that contains information about the Iowa roadway network allowed a relatively easy calculation and comparison of various safety measures related to each dataset. For example, statewide WVC and deer carcass removal frequencies and rates are shown in Table 15 for the three-year analysis time period. In addition, the combined number of deer carcasses removed by the IaDOT and those salvaged through the Iowa Department of National Resources (IaDNR) is shown. About 34% of roadside deer carcasses are salvaged under permit from the state. Sixty-six percent of the roadside deer carcasses are removed by IaDOT and their location noted (these are the removals plotted in Figure 4 and Figure 5). According to the IaDNR, the roadway locations for the deer carcasses they permit for salvage are not consistently collected, and should therefore not be used for analysis.

Table 15: Statewide wildlife-vehicle crash and deer carcass removal measures (2001 to 2003)

Measure	WVC	Carcass Removals[1]	Salvaged and Unsalvaged Deer Carcasses[2]
Total	23,094	25,258	38,283
Per Year	7,698	8,419	12,761
Per Roadway Mile	0.20	0.22	0.34
Rate per Hundred Million Vehicle-Miles-of-Travel	25.3	27.6	41.9

[1]Deer carcass removals are those recorded and summarized by the Iowa DOT by location
[2]Salvaged and unsalvaged deer carcasses are summarized by Iowa Department of National Resources. The Department of Transportation deer carcass removals are a portion of this total, but the only removals for known roadway location

The numbers in Table 15 are general statewide measures and when recalculated for individual roadway segments often are different (Table 16). The data in Table 15 illustrate three statewide databases that provide different values for the WVC data in Iowa. The number of deer carcasses removed by IaDOT, for example, is approximately

1.09 times greater than the number of WVCs reported to the police. The number of salvaged and unsalvaged deer carcasses, on the other hand, is approximately 1.66 times greater. The other safety measures in Figure 16 show a similar trend. However, only the WVCs and deer carcass removals in Table 15 are related to roadway location in Iowa, and typically the location of the latter is not known. The plots in Figure 4 and Figure 5 show that their patterns are also different. The use of different databases could lead to different statewide policy and corridor level decisions related to WVC problem. In addition, the choice of the database used could lead to different conclusions.
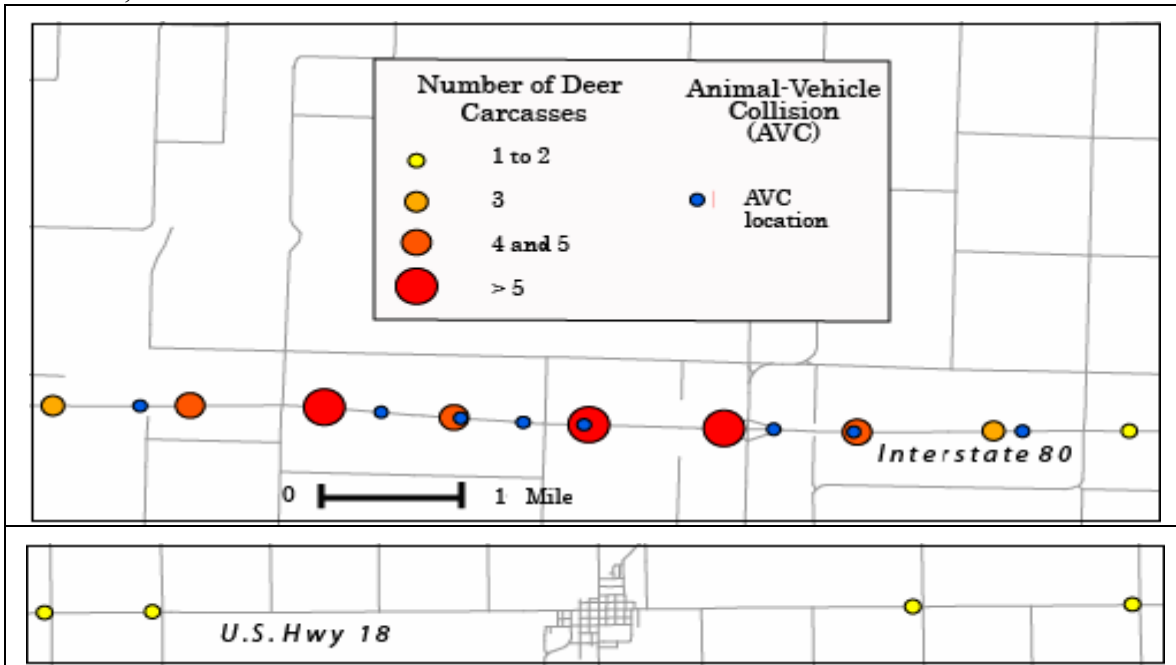
Figure 5: Deer carcass removal and WVC locations I-80 and U.S. Highway 18 in 2002

Figure 5 shows the reported WVCs and deer carcass removals for sample roadway segments along Interstate 80 and U.S. Highway 18 in Iowa. A more detailed summary of the safety measures describing the WVCs and deer carcass removals along these two segments, is shown in Table 16. These measures could be compared to the statewide results in Table 15 and/or those calculated for roadways with similar characteristics (See Table 10).

Table 16: Example roadway segment WVC and deer carcass removal measures (2001 to 2003)

Safety Measures	I-80 Wildlife-vehicle Crashes (8.4 Miles)	I-80 Deer Carcass Removals (8.4 Miles)	U.S. Highway 18 Wildlife-vehicle Crashes (9.9 Miles)	U.S. Highway 18 Deer Carcass Removals (9.9 Miles)
Total Number	19	163	5	19
Rate / Year	6.3	54.3	1.7	6.3
Rate / Roadway Mile	2.3	19.3	0.51	1.9
Rate / Hundred Million-Vehicle-Miles-of-Travel	10.4	89.6	17.2	65.4

[1]See Figure 5 for plots of 2002 wildlife-vehicle crash and deer carcass removals along these segments in Iowa

The results of this type of general comparison can be used as a filter to determine whether a particular roadway segment should be considered in more detail.Figure 4 and Figure 5 show that reported WVCs and deer carcass removals have different locational patterns. This lack of similarity could lead to the implementation of countermeasures along different roadway segments. Table 16 summarizes the WVC and deer carcass removal data from 2001 to 2003 for the roadway segments shown in the Figure 5. The differences in the magnitude of the WVCs and deer carcass removals that occur along these roadway segments are clear. Overall, the number of carcasses removed along the Interstate 80 segment was 8.6 times greater than the number of WVCs reported. The number of carcasses collected along U.S. Highway 18, on the other hand, was 3.8 times greater than the number of reported WVCs.

More than 90% of the Interstate 80 segment length summarized in Table 14 (and shown in Figure 5) was classified as a four-lane rural roadway. The frequencies and rates in Table 16 are all generally greater than the statewide measures for a roadway with these characteristics. Only the use of an WVC rate might lead to the conclusion that this segment has a typical WVC data level. The U.S. Highway 18 segment in Figure 5 is primarily a two-lane rural roadway. Mixed conclusions result when the WVC and deer carcass removal measures for this roadway (See Table 16) are compared to relevant statewide measures. The WVCs and deer carcasses removals per mile along the segment are larger than the statewide measures, but the rates (based on volume) are both smaller than those calculated for the entire state. Clearly, the choice of the data (WVCs or deer carcass removals) and safety measure (e.g., per mile or rate) used impacts whether a particular roadway segment might be identified for closer consideration. The comparisons described above consider average values, but more "critical" frequency and/or rates could also be used as an initial step to 'hot spot' roadway segment identification.

Crash and carcass model development and comparison—Prediction models using WVC, deer carcass removal, and roadway cross section data from Iowa were developed to assist in the identification of potential "hot spot" roadway segments. These models are described next, and they can be applied in a manner similar to those described later in this report. In any case, a site visit to each potential "high" crash or carcass segment is necessary for confirmation purposes and the identification of specific countermeasure installation locations. This section of the safety analysis report focuses on the differences between models developed from WVC and deer carcass removal data and the potential impact of those differences.

The combination of WVC, deer carcass removal, and roadway location data in a GIS platform allowed the production of WVC and deer carcass removal prediction models to describe the relationships between the occurrence of an WVC or removal and several roadway cross section characteristics typically available through DOT databases. The data used for model development are described elsewhere in this report.

The prediction models created as part of this analysis were for rural paved two-lane and multi-lane roadways in Iowa with a State Route, U.S. Route, or Interstate designation. The WVC, deer carcass removal, and roadway cross section data used to create these models were from 2001, 2002, and 2003. The methodologies and model-building approaches followed were similar to those earlier in this report. The SPFs

developed for this project can be applied within an empirical Bayesian approach to predict the number of WVCs or carcass removals expected at a location.

Negative binomial models or SPFs were created to predict WVCs or deer carcass removals per mile-year. The rural two-lane and multi-lane models developed, and their details, are shown in Table 17 and Table 18. Prediction models with only average annual daily traffic are also provided later in this section (Table 19). Volume-only models were developed for comparison and application purposes (if the data related to the input variables in the other models were not available). The variables considered for use in each of the models were selected from the Iowa roadway cross section database (which included more than 90 factors). The variables used are listed and defined below:

> **AADT**: Annual average daily traffic on roadway (vehicles per day in both directions)
> **AVGSHD**: Average of left- and right-shoulder widths on two-lane roadways
> **LANES**: Total number of through lanes present
> **LSHDWID**: Width of the left side or inside shoulder (nearest foot)
> **MEDTYPE**: Classified as none (0), unprotected (1) or positive barrier (2)
> **MEDWID**: Width of the median between the edges of traffic lanes (nearest foot)
> **RSHDWID**: Width of the right side or outside shoulder (nearest foot)
> **SPEED**: Posted speed in miles per hour
> **SURFWID**: Surface width of roadway measured from edge of pavement to edge of pavement (feet)

The form and content of the WVC and deer carcass removal prediction models developed for rural two-lane roadways in Iowa are shown in Table 17. A comparison of these models shows that they include the same statistically significant variables. These variables include AADT and average shoulder width. The model coefficients for both models are also shown in Table 17 along with their standard error and the model overdispersion parameter. The impact of the variables in each model is somewhat different, and the explanatory value of the WVC model appears to be greater than the deer carcass removal model. The dispersion parameter of the deer carcass removal model, however, is high and this should be considered when it is applied. The differences in these models further support the conclusion that the use of WVC or deer carcass removal data can result in the identification of different roadway segments for potential countermeasure implementation. Of course, some of the differences shown in Table 17 are due to the differences in the locational accuracy of the information provided for the two databases and included in the GIS platform. These accuracies, however, are typical.

WVC and deer carcass removal prediction models were also developed for rural multi-lane roadways in Iowa. The model coefficients for both models are shown in Table 18 as are their standard errors and the model dispersion parameters. There are more

Table 17: Models for rural two-lane roadways (segments ≥ 0.1 mile) in Iowa

Model Dependent Variable	Model Form: Total wildlife-vehicle crashes or deer carcass removals per mile-year = $\exp(\beta_0)(AADT)^{\beta_1}\exp(\beta_2 SPEED + \beta_3 SURFWID + \beta_4 AVGSHD)$					
	β_0 (s.e.)	β_1 (s.e.)	β_2 (s.e.)	β_3 (s.e.)	β_4 (s.e.)	Dispersion Parameter
WVCs/Mile-Year	-5.9297 (0.2088)	0.6189 (0.0283)			0.0194 (0.0067)	1.0217
Deer Carcass Removals/ Mile-Year	-5.3097 (0.2930)	0.5626 (0.0399)			0.0693 (0.0096)	5.2768

differences in these models than those produced for the two-lane rural roadways. The models in Table 18 contain different variables. Both models include AADT, right shoulder width, and median width, but only the deer carcass removal model includes posted speed limit, left shoulder width, and median type. The explanatory value of the models is very different. The multi-lane WVC model has the lowest dispersion factor of all four models in Table 17 and Table 18 and the multi-lane deer carcass removal model has the highest dispersion factor. The results of this model development activity further support the importance of choosing the appropriate database to evaluated collision problem locations. The dispersion parameter of the deer carcass removal model is high and this should be considered in the application of this model.

Table 18: Models for rural multi-lane roadways (segments ≥ 0.1 mile) in Iowa

Model Dependent Variable	Model Form: Total wildlife-vehicle crashes or deer carcass removal per mile yr= $\exp(\beta_0)(AADT)^{\beta_1}\exp\left(\beta_2 SPEED + \beta_3 LANES + \beta_4 SURFWID + \beta_5 RSHDWID + \beta_6 LSHDWID + \beta_7 MEDWID\ H + \beta_8 MEDTYPE\right)$									
	β_0 (s.e.)	β_1 (s.e.)	β_2 (s.e.)	β_3 (s.e.)	β_4 (s.e.)	β_5 (s.e.)	β_6 (s.e.)	β_7 (s.e.)	β_8 (s.e.)	Dispersion Parameter
WVCs/ Mile-Year	-1.1241 (0.3265)	0.0684 (0.0350)				0.0332 (0.0194)		0.0011 (0.0005)		0.6268
Deer Carcass Removals/ mile-year	-6.4836 (0.8548)	0.6445 (0.0844)	0.0200 (0.0099)			0.1183 (0.0485)	-0.0788 (0.0439)	0.0040 (0.0017)	-1.0957 (0.2626)	7.4753

Finally, WVC and deer carcass removal models, with AADT as the only input variable, were also developed. These models are shown in Table 19. They were created for application if the data for the roadway cross section variables in the previous models

(See Table 15 and Table 16) were not available. In addition, the volume-only models were compared to the other models developed to investigate the additional explanatory value offered by the addition of more cross section variables. A comparison of the dispersion parameters in Table 19 with those in Table 15 and Table 16 reveals that the inclusion of other roadway cross section variables in the models adds little to the predictive strength of the WVC and deer carcass removals models. In other words, the AADT traffic flow measure contains most of the explanatory value of these models. Overall, the explanatory value of the WVC models with only AADT is still better than those developed with deer carcass removal data. Some of this difference, as previously stated, is due to the inconsistency in the locational accuracy of the two datasets. The high dispersion parameters of the deer carcass removal models in Table 19 should be noted.

Table 19: Volume-only models (segments ≥ 0.1 mile) IN ioWA

Model Dependent Variable	Model Form: Total wildlife-vehicle crashes or deer carcass removals per mile-year = $\exp(\beta_0)(AADT)^{\beta_1}$		
	β_0 (s.e.)	β_1 (s.e.)	Dispersion Parameter
Rural Two-Lane Roadway			
WVCs/Mile-Year	-5.9986 (0.2078)	0.6465 (0.0268)	1.0243
Deer Carcass Removals/ Mile-Year	-5.4655 (0.2930)	0.6509 (0.0381)	5.3510
Rural Multi-Lane Roadways			
WVCs/Mile-Year	-1.0429 (0.3075)	0.1007 (0.0330)	0.6300
Deer Carcass Removals/ Mile-Year	-4.4484 (0.6137)	0.5509 (0.0662)	7.5987

Interpretation, Appraisal, and Applications

Aspect 1: Application of reported wildlife vehicle collision data

As they stand, the primary application of the models is for the safety management of existing roads as opposed to design or planning applications for new or newly built roads. For existing roads, wildlife-vehicle crash data are available and used, along with the model predictions in an empirical Bayes procedure to estimate the expected long-term mean crash frequency of a specific roadway segment. Three types of applications of the models are summarized and illustrated in the sections to follow. These are the applications that would be most relevant to the development of the desired guidelines. They include:

1) Network screening to identify roadway segments that may be good candidates for wildlife-vehicle colllision countermeasures
2) Evaluation of the effectiveness of implemented countermeasures
3) Estimation of the effectiveness of potential countermeasures

Network screening to identify roadway segments that may be good candidates for wildlife-vehicle colllision countermeasures— Two fundamental methodologies are presented and illustrated for this application:

1) Identifying and ranking sites based on a high expected frequency of wildlife-vehicle colllisions
2) Identifying and ranking sites based on a high proportion of wildlife-vehicle colllisions

SPFs are used in the first application. The second applies for situations where an SPF may not be available or applicable.

Identifying and ranking sites based on a high long-term frequency of wildlife-vehicle colllisions—As noted earlier the short term collision count at a location is not a good estimate of its safety. Thus, identifying and ranking crash prone locations based on short term counts will be inefficient. Longer term crash frequencies are now recognized as the best basis for identifying and ranking these locations.

The long-term frequency of wildlife-vehicle colllisions at a site is obtained by using the empirical Bayes (EB) methodology that combines the site's wildlife-vehicle colllision frequency with the frequency expected by applying the safety performance functions described earlier. In this approach, overlapping segments of equal length should be considered in what is often termed a 'sliding window' approach. A brief overview of the method is provided with an example calculation. When the *SafetyAnalyst* (www.safetyanalyst.org) software becomes available there will be a facility to consider segments of different length using a sophisticated 'peak searching' algorithm.

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected at locations with traffic volumes and other characteristics similar to the ones being analyzed. The estimate, P, is then combined with the count of crashes (x) observed to obtain an estimate of the expected number of crashes (m). This estimate of m is:

$$m = w_1(x) + w_2(P),$$

where the weights w_1 and w_2 are estimated from the mean and variance of the SPF estimate as:

$$w_1 = P/(P + 1/k)$$

$$w_2 = 1/k/(P + 1/k),$$

and where k is the dispersion parameter for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In this process, a negative binomial distributed error structure is assumed with k being the dispersion parameter of the distribution. For network screening purposes each segment is then ranked in descending order by the expected number of crashes (m).

As an illustration, suppose that the two-lane rural roads in Utah are divided into one mile WVC segments that may or may not overlap. Consider one such segment for which the following information applies:

length = 1 mile (1.6 km)
16 years of data
40 wildlife-vehicle colllisions observed
average AADT of 2,066

First, the UT 1 model from Table 12 is used for this example to calculate the regression estimate P.

$$P = (years)(length)\alpha(AADT)^{\beta_1}$$
$$P = (16)(1)\exp(-9.1135)(2{,}066)^{1.0237} = 4.36$$

Next, the weights w_1 and w_2 are calculated.

$$w_1 = 4.36/(4.36 + 1/1.7610) = 0.88$$

$$w_2 = 1/1.7610/(4.36 + 1/1.7610) = 0.12$$

Lastly, the regression estimate, P, and the observed collision count, x, are combined.

$$m = 0.88(40) + 0.12(4.36) = 35.72$$

The EB estimate of the expected number of collisions during the 16 year period is 35.72, lower than the observed count of 40. This EB estimate is used in ranking this location relative to the other one-mile segments.

Identifying and ranking sites based on a high proportion of animal–vehicle collisions—Where traffic volume and other characteristics necessary to estimate the expected crash frequency at a site are unavailable, identifying sites with a high proportion of animal–vehicle collisions might be appropriate. This method uses the observed counts for animal–vehicle collisions and all collisions at a site but adjusts for the 'noise' in each of these counts. For example, one is more certain that the proportion is high for a site with 20 animal–vehicle crashes out of 30 crashes than for a site with 2 out of 3 crashes. The theory behind this method is described in Appendix C. Of particular note is that the method only requires the counts of animal–vehicle and all collisions at sites to be screened (i.e., SPFs are not required). This method is also being implemented in *SafetyAnalyst.*

By way of illustration, the Utah 2-lane rural roadway dataset is used. The data were manipulated into 1 mile long segments, although any desired length could be

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considered. The top twenty sites ranked using the EB estimate of mean animal-collision frequency outlined earlier are presented in Table 20.

Table 20: Comparison of alternate ranking methods

Site	Rank by EB method	Rank by Proportions method
11430	1	9
10194	2	6
9463	3	3
10336	4	48
11546	5	11
9947	6	4
9154	7	2
10177	8	5
6749	9	1
6716	10	35
11545	11	19
11554	12	12
10195	13	7
10197	14	8
11432	15	47
6697	16	28
9477	17	920
10673	18	18
6752	19	80
6694	20	86

The same segments were also screened based on the probability that their proportion of wildlife-vehicle colllisions is greater than 20.7%, the mean proportion for all segments. The rankings from this 'proportions' method are shown in the last column of Table 20. As seen, seven of the top 10 segments identified by the EB method were also in the top 10 ranked by the proportions method. Thirteen of the top 20 segments identified by the EB method were also in the top 20 ranked by the proportions method. It appears that ranking by a high proportion of wildlife-vehicle colllisions may be a reasonable alternative to ranking by the EB estimate of wildlife-vehicle colllisions should the required data or resources not be available for developing or applying SPFs.

Evaluation of the safety effectiveness of mitigation measures, specifically the installation of animal crossings—The methodology for the conduct of a proper observational before-after study is well documented in a landmark book by Hauer.[114] The statistically defendable before-after analysis methodology proposed overcomes the difficulties associated with simple before-after comparisons of collision counts. The proposed methodology:

1) Properly accounts for regression-to-the-mean
2) Overcomes the difficulties of using crash rates in normalizing for traffic volume differences between the before and after periods

3) Reduces the level of uncertainty in the estimates of safety effect
4) Provides a foundation for developing guidelines for estimating the likely safety consequences of installing a crossing and fencing
5) Properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions

The task is to estimate what was the effect on safety of installing wildlife crossing measures. In this, "safety" is the expected number of wildlife-vehicle crashes per unit of time for a road segment of interest. To do this requires three steps.

STEP 1. Predict what safety would have been during the "after" period, had the status quo been maintained

STEP 2. Estimate what safety was during the after period with crossing measures in place

STEP 3. Compare the two

The following approach to STEP 1 (predicting what safety would have been during the 'after' period had the status quo been maintained) is suggested.

1) Account explicitly for the effect of changes in traffic flow by using an SPF
2) Account for the effect of weather, demography, other variables by using a comparison group to recalibrate the SPFs to be used
3) Account for possible selection bias (regression-to-the-mean effects) and improve estimation accuracy by the empirical Bayes (EB) method using the best available methodology.[114]

In the EB approach, the change in safety for a given crash type is given by:

$$\lambda - \pi$$

where λ is the expected number of crashes that would have occurred during the after period without the crossing measures and π is the number of reported crashes during the after period.

In estimating λ, the effects of regression to the mean and changes in traffic volume are explicitly accounted for by using safety performance functions (SPFs) relating crashes of different types and severities to traffic flow and other relevant factors for each jurisdiction based on locations without crossing measures.

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected during the before period at locations with traffic volumes and other characteristics similar to the one being analyzed. The estimate, P, is then combined with the count of crashes (x) during the before period at a treatment site to obtain an estimate of the expected number of crashes (m) before the crossing measures were installed. This process is identical to that presented earlier, but is repeated here for completeness. This estimate of m is:

$$m = w_1(x) + w_2(P)$$

where the weights w_1 and w_2 are estimated from the mean and variance of the SPF estimate as:

$$w_1 = P/(P + 1/k)$$

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$$w_2 = 1/k/(P + 1/k)$$

and where k is the dispersion parameter for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In that process, a negative binomial distributed error structure is assumed with k being the dispersion parameter of this distribution.

The variance of the estimate m is:

$$Var(m) = ((x+1/k)P^2)/(1/k+P)^2$$

A factor f is then applied to m to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the value of the SPF prediction for the after period divided by P:

$$f = \text{sum of SPF predictions post treatment}/P$$

The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

$$Var(\lambda) = (f/P)^2 Var(m)$$

The estimate of λ is then summed over all locations in a treatment group of interest (to obtain λ_{sum}) and compared with the count of crashes during the after period in that group (π_{sum}). The variance of λ is also summed over all sections in the treatment group.

The Index of Effectiveness (θ) is estimated as:

$$\theta = (\pi_{sum}/\lambda_{sum}) / \{1 + [Var(\lambda_{sum})/\lambda_{sum}^2]\}$$

The standard deviation of θ is given by:

$$Stddev(\theta) = [\theta^2\{[Var(\pi_{sum})/\pi_{sum}^2] + [Var(\lambda_{sum})/\lambda_{sum}^2]\} / [1 + Var(\lambda_{sum})/\lambda_{sum}^2]^2]^{0.5}$$

The percent change in crashes is in fact $100(1-\theta)$; thus a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12%.

As an illustration of the method, Table 21 presents the results of an analysis for two sites located in Utah (Route 40 between mileposts 4.0-8.0, and Route 248 between mileposts 3.3-13.5). Each site involved the construction of one or more At-Grade wildlife crossings and continuous exclusion fencing which extended beyond the limits of the crossings themselves. Note that the roadway inventory data has divided these sections of the road into multiple sub-segments due to differences in number of lanes, AADT, and other variables.

The results for the demonstrative case indicate an wildlife-vehicle crash reduction of:

$$(1-0.702)*100 = 29.8\% \text{ with a standard error of } 9.1\%$$

Note that this result is based on only two sites in one state and thus should not be used as conclusive evidence of the safety benefits of installing wildlife crossings and fencing.

Estimating the cost effectiveness of a potential mitigation measure such as a crossing—The objective is to provide designers and planners with a tool to estimate the

change in wildlife-vehicle crash frequency expected with the installation of wildlife crossings and fencing at a segment of roadway under consideration.

For the approach, an SPF representative of the existing road segment is required. This will require that a SPF exists for the jurisdiction, or that data are available to enable a recalibration of a model calibrated for another jurisdiction. The SPF would be used, along with the segment's crash history, in the empirical Bayes procedure to estimate the expected crash frequency with the status quo in place, which would then be compared to the expected frequency should a crossing and fencing be constructed to estimate the benefits.

Step 1:
Assemble data and crash prediction models for road segments.
1. Obtain the count of wildlife-vehicle crashes
2. For each year obtain or estimate the average AADT
3. Estimate the AADT that would prevail for the period immediately after construction

Step 2:
Use the EB procedure documented earlier, with the data from Step 1, and the road segment model to estimate the expected annual number of wildlife-vehicle crashes that would occur without construction of the crossing and fencing.

Step 3:
Apply a Crash Modification Factor (CMF) to the expected crash frequency with the status quo in place to get expected benefit in terms of the number of annual wildlife-vehicle crashes expected to be reduced. A CMF is an adjustment to the estimate based on the expected reduction in WVC. Until a reliable CMF can be determined from properly conducted before-after studies an interim CMF could be developed through an expert panel as has been done for other roadway safety countermeasures.[113]

Step 4:
Compare against the cost, considering other impacts if desired, and using conventional economic analysis tools. The results of the analysis above may indicate that crossing structures are justified based on a consideration of safety benefits. This should not be taken to mean that crossings should be constructed, since:

a) Other measures may have higher priority in terms of cost effectiveness
b) The safety benefits may need to be assessed in the light of other impacts
c) Other locations may be more deserving of a crossing. In other words, the results of the above analysis should be fed into the safety resource allocation process.

Table 21: **Illustration of EB before-after study**

Site	No. of Lanes	Length	Years Before	Years After	AADT Before	AADT After	Crashes Before (x)	Crashes After (π)	Sum of SPF Predictions After	k	w1	w2	m	λ	Var (m)	Var (λ)
1	4	2.04	9	6	7654	13227	39	18	18.85	1.53	0.97	0.03	38.52	32.69	37.42	26.96
1	4	1.96	9	6	7450	13227	45	47	18.11	1.53	0.97	0.03	44.28	38.04	42.96	31.69
2	2	0.05	4	6	2630	7493	1	1	0.36	1.76	0.13	0.87	0.20	0.87	0.03	0.48
2	2	0.19	4	6	2630	7493	0	0	1.37	1.76	0.36	0.64	0.20	0.88	0.07	1.38
2	2	0.58	4	6	2630	7493	2	5	4.19	1.76	0.63	0.37	1.61	7.06	1.01	19.39
2	3	0.18	4	6	2630	7493	0	2	1.30	1.76	0.34	0.66	0.19	0.85	0.07	1.28
2	4	0.21	4	6	2630	7493	3	2	1.24	1.53	0.44	0.56	1.62	3.86	0.72	4.07
2	4	0.12	4	6	2553	7493	3	2	0.71	1.53	0.31	0.69	1.13	2.73	0.35	2.04
2	4	1.40	4	6	1707	3375	3	6	5.80	1.53	0.81	0.19	2.97	6.03	2.42	9.95
2	4	0.07	4	6	1707	3375	0	0	0.29	1.53	0.18	0.82	0.12	0.24	0.02	0.09
2	4	0.42	4	6	1707	3375	4	2	1.74	1.53	0.57	0.43	2.64	5.36	1.50	6.17
2	3	2.70	4	6	1707	3375	16	17	8.62	1.76	0.83	0.17	13.82	41.66	11.53	104.77
2	4	0.34	4	6	1707	3375	8	2	1.41	1.53	0.52	0.48	4.47	9.05	2.30	9.46
2	4	0.08	4	6	1707	3375	0	1	0.33	1.53	0.20	0.80	0.13	0.26	0.03	0.11
2	3	3.09	4	6	1707	3375	10	21	9.86	1.76	0.85	0.15	9.00	27.14	7.67	69.71
2	2	0.77	4	6	1707	3375	0	0	2.46	1.76	0.59	0.41	0.33	1.01	0.20	1.79
							SUM	126					121.26	177.74		289.36

θ	0.702
VAR(θ)	0.008
S.E.(θ)	0.091

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Illustration
STEP 1: Assemble data and crash prediction models.

A 2 mile long section of road, with data from 1998 to 2002, is being considered for the construction of a wildlife crossing and fencing along the entire section. This section experienced 18 animal–vehicle collisions during this time period. The average AADT was observed to be 5,000 and is assumed to increase by 5% following the proposed construction, although this anticipated increase in traffic is not related to the contemplated construction. The appropriate SPF is:

$$P = (years)(length)\exp(-9.1135)(AADT)^{1.0237} ; \text{k=1.6098}$$

STEP 2: Use the EB procedure to estimate the expected annual number of wildlife-vehicle crashes that would occur without construction of the crossing and fencing.

$$P = (5)(2)\exp(-9.1135)(5{,}000)^{1.0237} = 6.74$$

$$w_1 = 6.74/(6.74 + 1/1.6098) = 0.92$$

$$w_2 = 1/1.6098/(6.74 + 1/1.6098) = 0.08$$

Lastly, the regression estimate, *P*, and the observed collision count, *x*, are combined.

$$m = 0.92(18) + 0.08(6.74) = 17.1, \text{ or } 3.4/ \text{ year}$$

It can be seen that the combination of a high dispersion parameter, k, and relatively long length of the segment leads to a relatively high weight being given to the SPF estimate P.

Because traffic is expected to increase 5% in the period after the contemplated construction the estimate *m* is adjusted by the ratio of the AADT term in the model:

$$m^* = 3.4*(5000*1.05)^{1.0237}/(5000)^{1.0237} = 3.57/\text{year}$$

STEP 3: An appropriate Crash Modification Factor (CMF) is applied to the estimate *m** to estimate the expected benefit in terms of the number of annual animal–vehicle crashes expected to be reduced. For this illustration assume that the expected reduction is 20% (i.e., that the CMF is (100-20)/100 = 0.8).

$$\text{Annual Benefit} = 0.20(3.57) = 0.71 \text{ animal–vehicle collisions}$$

STEP 4: Apply the estimated cost per crash to the estimate from Step 3 to estimate the dollar value benefit per year. Compare this benefit against the annualized cost of construction, maintenance and other relevant considerations.

Aspect 2: Comparison of wildlife-vehicle colllision and carcass removal data

The primary objective of this aspect of the safety data analysis was to investigate the hypothesis that the choice and application of reported WVC and carcass removal data as they might exist at a DOT could result in varying policies or WVC countermeasure-related roadway development decisions. One or both of these two databases have been used in the past to describe the magnitude of the WVC problem and to propose and evaluate the effectiveness of WVC countermeasures. Overall, the visual and quantitative findings of the reported WVC and deer carcass removal comparison activities revealed that both their magnitudes and patterns are different. This is important when choosing a database for public information purposes, future research activities, and countermeasure implementation/evaluation choices. The objectives of the activities and the validity of the databases available need to be considered.

The GIS figures, summary data, and models developed as part of this research could be useful to the IaDOT, but require recalculation and/or recalibration for application in other states. For example, the statewide safety measures in Table 15 and Table 16 can be used for an initial or gross comparison to the WVC or deer carcass removal experience along particular roadway segments. Potential 'hot spot' locations for WVCs or deer carcass removals might be defined initially for further examination. In the discussion below, we focus on the impact of the reported WVC and deer carcass removal comparison results rather then the direct application of the plots, measures, and models calculated. We discuss some of the challenges related to combining and presenting these data in a GIS platform.

WVC and carcass removal GIS activities—The combination of crash and carcass data within a GIS platform, if available by location, can be difficult. The importation of different datasets into a GIS platform requires the definition and compatibility of the systems used to locate these data. In this project, the objective was to have WVC and deer carcass removal information in the same GIS platform for comparison and modeling purposes. The locations of the WVCs were available in latitude and longitude for the three years considered, however, the deer carcass removal locations were estimated to the nearest 0.1 milepost, and then modified for budget and schedule purposes to the nearest milepost and summed. The differences in the spatial systems used to collect WVCs and deer carcass removal data did present a challenge when we tried to combine and plot them. For example, the deer carcass removals had to be plotted as proportional circles to represent the different number of removals at one location, but the reported WVCs (located by latitude and longitude) were plotted individually. As noted throughout this report, these differences in accuracy and data collection did have an impact on the comparison results. A similar accuracy and consistency in the collection of both types of data is desirable (it results in similar plotting), but is not currently typical at DOTs. The availability of WVCs, deer carcass removals, and roadway cross section information within a GIS platform did, however, allow a relatively easy summary, comparison, and modeling of the Iowa data.

Statewide, example corridor, and model comparisons—The statewide and sample transportation corridor reported WVC and deer carcass removal patterns in the GIS plots of this report are clearly different (Figure 4 and Figure 5). The difference becomes more obvious as smaller roadway segments (Figure 5) are considered. The plots

and safety measures calculated as part of this project also indicate that the two databases define the magnitude of the WVC problem differently. In addition, the prediction models developed for reported WVCs and deer carcass removals had different coefficients and/or input variables. The use of any of these tools to set WVC-related policies or determine potential locations for WVC countermeasures will likely produce different and possibly less efficient and effective results. The choice of safety measures (e.g., WVCs per year) may also impact the results of any comparison. It is important to understand the basis and defining criteria of the database(s) being considered.

Some of the difference in the reported WVC and deer carcass removal GIS plot patterns, safety measures, and models are the result of different data collection patterns and approaches (e.g., spatial accuracy and consistency). Another portion of the difference is likely due to the fact that more carcasses are often removed than WVCs reported to the police (i.e., the dataset size is different). For example, WVCs that result only in property damage are reported only if a minimum dollar amount of vehicle damage results (e.g.,≥ $1,000). Therefore, reported WVC data might best describe the more serious WVC events and carcass removal data the overall number of conflicts between vehicles and animals. Unfortunately, the reporting of WVCs (even if the minimum property damage requirement is met) appears to vary widely from state to state and carcass removal locations are not typically collected in any consistent manner. Whether one or both datasets can or should be used within a particular state needs to be decided on a case-by-case basis. As indicated earlier, similar accuracy and consistency in the collection of both types of data is desirable. This similarity allows the proper visual or quantitative combination and comparison of the databases.

Conclusions and Suggested Research

Ambitious objectives were set out in defining a plan of work for the safety data analysis for this project. These objectives were complementary to the overall project objectives to provide guidance in the form of clearly written guidelines for the selection of crossing types, their configuration, their appropriate location, monitoring and evaluation of crossing effectiveness, and maintenance. Significant progress has been made in achieving these safety data analysis objectives and this is summarized here as bulleted conclusions for this part of the project. Yet, further effort and consideration is needed because of limitations in data currently available to effectively address all of the objectives set out and because of the implications of some of the findings.

Recommendations for further work and considerations are identified in a separate subsection.

Aspect 1: Application of reported wildlife vehicle collision data
This aspect of the work involved the development of safety performance functions and illustrated their potential applications related to the objectives of the project, rather than investigative research. Nevertheless, a few conclusions may be drawn:

- Safety performance functions (SPFs) were successfully calibrated for four states (in addition to that calibrated for Aspect 2) to relate police reported wildlife vehicle collisions (WVC) to variables normally available in state DOT databases.

For these functions, AADT is the dominant variable, with additional significant variables such as speed, lane and shoulder width, and median type, making relatively small contributions to the explanatory power of the SPFs

- The SPFs vary considerably across states in terms of the effect of the key AADT variable
- The empirical Bayes procedure can be used to combine SPF predictions with WVC history to better estimate a location's safety in accounting for key factors such as animal movements not in the SPFs
- The EB estimate can be used for screening the road network to identify candidate locations for WVC countermeasures. However, for situations where SPFs, or the resources required to calibrate them, are not available, a method that ranks locations according to their proportion of WVCs can produce reasonable results

An illustration was presented of the application of safety performance functions in an empirical Bayes before-after study of safety effectiveness of a wildlife crossing installation. Sufficient installation data were not available to enable the formal study that was envisaged.

Aspect 2: Comparison of wildlife-vehicle colllision and carcass removal data

The following conclusions are based on the data combination, comparison, and analysis activities previously described. The general objective of these activities was to visually and quantitatively determine whether the use of WVC and deer carcass removal data might lead to the identification of different roadway segments for potential countermeasure implementation.

- Police-reported WVC and/or deer–vehicle crash (DVC) data by roadway location are available throughout the United States, but animal or deer carcass removal data by location is rarely collected and/or summarized. The latter data may sometimes be available for short periods of time and/or for specific roadway segments, but is not typically collected consistently throughout a state for many years. Both of these databases can be used to define the WVC problem, but the results will often differ.
- The WVC and deer carcass removal data used in this research was obtained from the Iowa Department of Transportation. These two datasets were collected with different methods and at different levels of accuracy. This situation is not surprising, but it did lead to some challenges related to their combination and comparison in a GIS platform. The WVC data from 2001 to 2003 was available by latitude and longitude, but the deer carcass removal locations were adjusted to the closest milepost and summed. The impacts of modifying the deer carcass removal locations on the results of this research are noted where appropriate.
- A quantitative summary of the 2001 to 2003 WVC and deer carcass removal data used in this research confirmed that there is a difference in their magnitude. There are more deer carcasses removed then WVCs reported. In addition, and not surprisingly, the WVC and deer carcass removal data are collected from different type of roadways. IaDOT primarily removes deer carcasses from Interstates, and U.S. Routes. A greater percentage of the police-reported WVCs occur on Farm to Market Routes and local roadways.

- A visual comparison of statewide and regional WVC and deer carcass removal plots support the hypothesis that the data from these two databases may result in the identification of different roadway segments as potential locations of concern. A similar comparison along specific segments of Interstate 80 and U.S. Route 18 resulted in the same conclusion. A quantitative comparison of the WVC and deer carcass removal safety measures along these segments to relevant statewide calculations also supported the conclusion that the choice of dataset (e.g., WVC or deer carcass removal) does matter. In addition, and not surprisingly, the choice of the safety measure used in the comparison also has an impact. The data used, type of safety measure calculated, and the analysis approach applied all impact the "high" collision locations identified. Again, some of the differences observed in the data and the models developed are due to the dissimilarity in the accuracy and plotting approach of the WVC and deer carcass removal data used.

- WVC and deer carcass removal regression models were created for rural two-lane and multi-lane roadways. The two-lane rural roadway models contain the same variables, but the rural multi-lane roadway WVC and deer carcass removal models have different variables. The results of these WVC and deer carcass removal prediction models would be different for the same roadway segment. This difference could impact decisions related to countermeasure implementation. Overall, the WVC models generally had better explanatory value than the deer carcass removal models, and the deer carcass removal models should be used with caution due to their high overdispersion parameters. The WVC and deer carcass removal models that included only AADT did not appear to be dramatically different in their predictive capability than the models that included additional cross section variables. The proper use and calibration of these models is explained in Sections 2 and 4 of this report and the appendices.

Recommendations

Aspect 1: Application of reported wildlife vehicle collision data
- Empirical Bayes procedures, using safety performance functions presented and police reported WVCs (where accurate carcass removal data are unavailable) should be used for several tasks related to the project objectives. These are:
    - Evaluation the safety effectiveness of wildlife crossing installation and other WVC countermeasures
    - Network screening to identify candidate locations for WVC countermeasures
    - Estimating the cost-effectiveness, specifically the safety benefits of a contemplated wildlife crossing or other WVC countermeasure.
- Sufficient data should be collected to enable a full study of the safety effectiveness of crossings installed, using the methodology illustrated above. A minimum of 20 installations should provide useful results.
- An expert panel, similar to those conducted recently for traffic engineering countermeasures under NCHRP 17-25, should be convened to develop crash modification factors for WVC countermeasures. These factors are used to

estimate the safety benefits of a contemplated wildlife crossing or other WVC countermeasure.

- For application in states other than those for which SPFs are presented, it is most desirable to develop SPFs for that state's data. Where this is not possible, an SPF from one of the four states for which SPFs are presented can be applied, but it should be recalibrated to reflect differences across time and space in factors such as collision reporting practices, weather, driver demographics and wildlife movements. A procedure for doing this recalibration is presented in Appendix A. In deciding which of the four models is best to adopt for another state it will be necessary to conduct some goodness of fit tests. A summary of these tests is presented as part of Appendix B.

Aspect 2: Comparison of animal–vehicle collision and carcass removal data

- It should be recognized that the use of police-reported WVCs to identify potential countermeasure locations may only define a portion of a statewide or corridor-specific animal collision problem. The locations identified as "high" reported WVC locations may not be the same as those identified as "high" animal or deer carcass removal locations.
- It is recommended that the collection of statewide or corridor-specific WVCs or DVCs *and* large-animal carcass removal locations be considered to define the magnitude and patterns of the safety concerns related to this issue. The consistent collection of both types of data with the same locational accuracy is desirable.
- It is recommended that, if feasible and available, both WVCs or DVCs and large-animal carcass removal locations be used in combination to help define the magnitude and patterns of this safety concern both statewide and along specific corridors. However, the double counting of animal–vehicle collisions should be avoided; e.g., one should ignore deer carcass removals that occur at the same time and location as a reported WVC or DVC. In this case, the attributes collected with the animal or deer removal (e.g., gender, estimated age, and species) might be transferred, if possible, to the reported WVC database.

- It is recommended that the models developed in this research be used only after appropriate calibration, and that the limitations of the models be understood. The results of these models should be appropriately applied within an empirical Bayesian approach. The empirical Bayesian approach and model calibration of these types of models are explained within several sections and appendices of this report. The development of animal or deer collision models with more reported and carcass removal data is also recommended. Models that adjust for the severity of large animal or deer collisions may also be useful (if there is enough variability in this crash characteristic). In general, it might be assumed that deer or animal carcass removals that were not the result of a reported WVC or DVC were likely the outcome of a 'less than reportable' property-damage-only collision.

LIMITING EFFECTS OF ROAD-KILL REPORTING DATA DUE TO SPATIAL INACCURACY (3.2)

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Abstract

To properly mitigate road impacts to wildlife and increase motorist safety, transportation departments need to be able to identify where individual animals, species, taxa, and vertebrate communities are susceptible to high road-kill rates along roads. Research on wildlife–vehicle collisions has demonstrated that they do not occur randomly but are spatially clustered.[190,124,51,134] The presence of wildlife tends to be linked to specific habitats and adjacent land use types. Thus, landscape spatial patterns would be expected to play an important role in determining road-kill locations and rates.[95] Explanatory factors of wildlife road-kills vary widely between species and taxa. Thus, to understand the importance of such factors and processes, it is first necessary to be able to measure and describe the spatial pattern of road-kill aggregations.

A variety of methods have been used by transportation and natural resource agencies to reduce road-related wildlife mortality.[201,191] However, the effectiveness of these mitigation measures is uncertain, as few studies have rigorously tested the efficacy of the suite of mitigation measures.[201] Measures of performance may include changes in the frequency of wildlife-vehicle collisions, and/or number of motor vehicle accidents (wildlife or non-wildlife related) before and after mitigation has been applied.[111] This is a problem because a reduction in collisions after mitigation may be due to lower opulation numbers. Because the function of wildlife crossings is to reduce road-related mortality and increase habitat connectivity for wildlife, performance measures will ultimately need to be combined to fully determine the conservation value of mitigation. Societal benefits of mitigation are measured in terms of savings in property damage from accidents when comparing adjacent sections of highway with and without mitigation in place.[51]

Through this project, researchers at the Western Transportation Institute (WTI) at Montana State University (MSU) utilized wildlife-vehicle collision carcass data to demonstrate how this information can be used to aid transportation management decision making and mitigation planning for wildlife. The team investigated the relative importance of factors associated with wildlife road-kills using two different datasets: one based on spatially accurate location data (< 3m error) representing an ideal situation; and a second dataset created from the first, that is characterized by high spatial error (≤ 0.5 mile or 800 m) and is likely typical of most transportation agency data. The goal of this project was to summarize how well these models identify causes of wildlife–vehicle collisions.

The primary result of this analysis was that an ungulate–vehicle collision (UVC) model, developed with spatially accurate location data, had high predictive power in identifying factors that contribute to collisions. Perhaps more noteworthy from this

exercise was the vast difference in predictive ability between the models developed with spatially accurate data and the less accurate data obtained from referencing UVCs to a mile-marker system. The results have important implications for transportation agencies that may be analyzing data that is referenced to a mile-marker system, or unknowingly is spatially inaccurate. These findings lend support to the development of a national standard for the recording of wildlife–vehicle collisions, as well as further research into new technologies that will enable transportation agencies to collect data that are more accurate.

This project also investigated the types of variables that explain wildlife–vehicle collisions, in particular whether they are associated with landscape and habitat characteristics or physical features of the road itself. In two different types of analyses, researchers identified that variables related to landscape and habitat were more significant than variables identified to road characteristics.

Introduction

Wildlife–vehicle collisions do not occur randomly along roads but are spatially clustered[190,124,51,134] because wildlife movements tend to be associated with specific habitats, terrain, and adjacent land-use types. Thus, landscape spatial patterns would be expected to play an important role in determining locations where the probability of being involved in an wildlife-vehicle collision is higher compared to other locations.[95] Explanatory factors of wildlife road-kill locations and rates vary widely between species and taxa. To properly mitigate road impacts to wildlife and increase motorist safety, transportation departments need to be able to identify where particular individuals, species, taxa, and vertebrate communities are susceptible to high road-kill rates along roads. Quality field data documenting locations and frequencies of wildlife–vehicle collisions can offer empirical insights to help address this challenging safety and ecological issue.

As part of maintaining state and provincial highway systems, transportation departments often collect information on the location of wildlife–vehicle collisions. Typically, maintenance personnel do not conduct routine surveys of animal road-kills, but instead collect information opportunistically while carrying out their daily work. Occasionally the information may be referenced to wildlife species and specific geographical landmarks such as 1.0-mile-markers or 0.1-mile-markers; however, it is commonly believed that opportunistically collected road-kill data are not spatially accurate. One study has shown that errors in road-kill reporting may be 500m or greater.[53] The inherent spatial error in most agency datasets limits the types of applications for which the data is useful in transportation planning and mitigation efforts.

In this report, we demonstrate how wildlife-vehicle collision carcass data can be analyzed to guide transportation management decision making and mitigation planning for wildlife crossings. We investigate the relative importance of factors associated with wildlife road-kills using two different datasets: one with highly accurate location data (< 3m error) representing an ideal situation and another dataset with high spatial error (≤ 0.5 mile or 800m), which is likely more characteristic of the dataset from the average transportation agency. We will illustrate how spatial accuracy of the data affects the

process of identifying variables that contribute to wildlife–vehicle collisions. Based on these outcomes, we make recommendations for collecting road-kill data more systematically and accurately, emphasizing the value of spatial accuracy in identifying and prioritizing problematic areas for highway mitigation projects. The intent of this effort is to provide an overview of considerations regarding the quality and application of wildlife–vehicle collision carcass data to aid in assessing and mitigating wildlife–vehicle collisions.
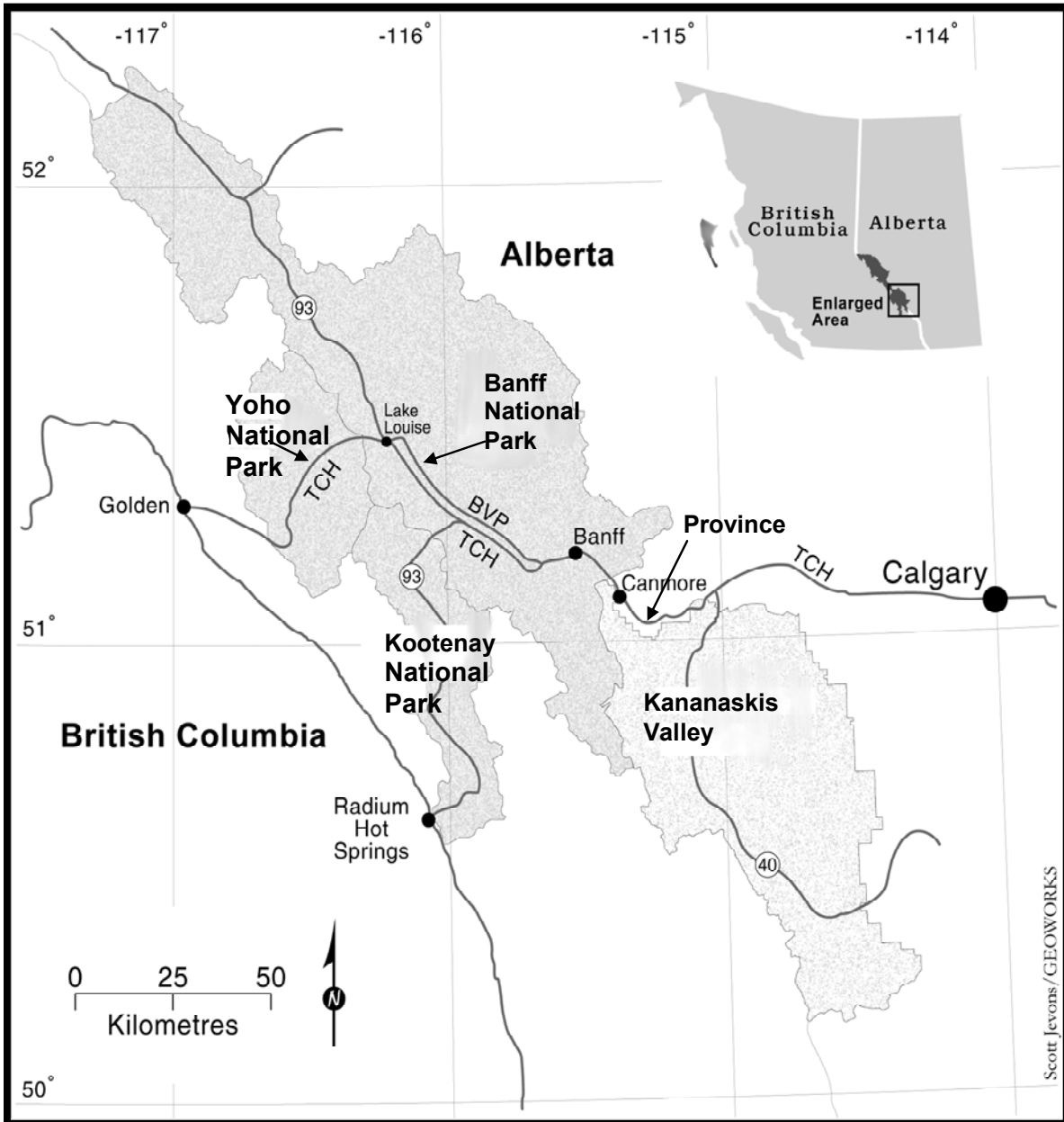
Figure 6: Location of Canadian study area

Study Area

     This study was conducted in the Central Canadian Rocky Mountains approximately 150km west of Calgary, straddling the continental divide in southwestern Alberta and southeastern British Columbia (Figure 6).The study area encompasses 11,400 km^2 of mountain landscapes in Banff, Kootenay, and Yoho national parks, and adjacent Alberta provincial lands. This region has a continental climate characterized by long winters and short summers.[121] Vegetation consists of open forests dominated by lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), white spruce (*Picea glauca*), Englemann spruce (*Picea englemannii*), quaking aspen (*Populus tremuloides*), and natural grasslands.

     Geology influences the geographic orientation of the major drainages in the region, characterized by valleys running north to south and delineated by steep shale mountains. On a regional scale, east-west movements of animals across and between these valleys are considered vital for long-term sustainability of healthy wildlife populations in the region. The transportation corridors associated with the major watersheds influence the distribution and movement of wildlife in the region. As the most prominent drainage, the Bow Valley accommodates the Trans-Canada Highway (TCH), one of the most important and, therefore, heavily traveled transportation corridors in the region.

     Highways in the study area traverse montane and subalpine ecoregions through four major watersheds in the region (Figure 6). Table 22 describes the location and general characteristics of the five segments of highways that were included in this study.

Table 22: Characteristics of the major highways in the Canadian study area

Highway	Watershed	Province	Road length (Km)	Traffic volume (ADT[1])	Posted vehicle speed (Km/hr)
Trans-Canada Highway	Bow River	Alberta, East of Banff National Park	37	16,960	110
Trans-Canada Highway	Bow River	Banff National Park, Alberta	33	8000	90
Trans-Canada Highway	Kicking Horse River	Yoho National Park, British Columbia	44	4600	90
Highway 93 South	Kootenay River	Kootenay National Park, British Columbia	101	2000	90
Highway 40	Kananaskis River	Alberta	50	3075[2]	90

[1]2005 annual average daily traffic volume. Data from Parks Canada Agency, Banff National Park and Alberta Transportation, Edmonton, Alberta

[2]1999 summer average daily traffic volume. Data from Alberta Transportation, Edmonton, Alberta

Research Approach: Methods and Data
Data Collection

Spatially accurate data set—In Sugust 1997, efforts were initiated to maximize data collection from carcasses resulting from wildlife–vehicle collisions (WVCs) and improve the spatial accuracy of reported locations of WVCs occurring on the highways in the study area. We worked with the agencies and highway maintenance contractors that were responsible for collecting and reporting wildlife carcasses, primarily elk. The agencies consisted of Parks Canada (Banff, Kootenay, and Yoho National Parks), Alberta Sustainable Resource Development (Bow Valley Wildland Park, and Kananaskis Country) and Volker-Stevin, maintenance contractor for the Trans-Canada Highway east of Banff National Park in the province of Alberta. This collaborative effort included national park wardens, provincial park rangers and maintenance crews of Volker-Stevin.

We provided colored pin-flags to carry in their vehicles to mark the sites in the right-of-way where road-killed wildlife were observed and collected. After placing a pin-flag, they were asked to report to us via telephone, fax, or email. Most wildlife carcasses were pin-flagged and reported within 48 hours.

The collaborators recorded the location of wildlife carcasses by describing the location with reference to a nearby landmark (e.g., 0.3km west of Banff National Park east entrance gate). Each reported WVC carcass site was re-located and confirmed by measuring the odometer distance from the reported landmark to the pin-flagged site. Once the location was confirmed, researchers recorded the actual location in Universal Transverse Mercator (UTM) grid coordinates using a differentially-correctable global positioning system (GPS) unit (Trimble Navigation Ltd., Sunnyvale, California, USA) with high spatial accuracy (< 3m). The UTM coordinates were recorded in a database along with the original date of each reported road-kill, and information regarding the species, sex, age, and number of individuals involved.

For this study, we used only ungulate carcass data (UVC), because ungulate species comprised 76% of the total wildlife mortalities. In addition, these species are often the greatest safety concern to transportation agencies given their size and relatively common occurrence in rural and mountain landscapes. Ungulate species included white-tailed and mule deer (*Odocoileus virginianus* and *O. hemionus*, respectively), unidentified deer (*Odocoileus sp.*), elk (*Cervus elaphus*), moose (*Alces alces*), and bighorn sheep (*Ovis canadensis*). The UVC data obtained from the methods described above are hereafter referred to as the 'spatially accurate' dataset and serve as a benchmark for the analysis.

Mile-marker data set—To investigate the influence that spatial accuracy and scale may have on the results and interpretation of the data, we created a 'mile-marker' dataset using the spatially accurate dataset, shifting each UVC location to the nearest hypothetical mile-marker. To do this, we divided each of the five highways in the study area into 1.0 mile-marker segments using ArcView 3.3.[77] All spatially accurate UVC data were plotted onto the road network and then moved to the nearest mile-marker reference point. Each observed data point was moved an average distance of 400.2 m ± 218.8 (min. 7.3, max 793.9) to its nearest mile-marker. We recorded the UTM coordinates of each

mile-marker location and summed the number of UVCs in that mile-marker segment, defined as 800m (0.5 mile) up and down the road of the given mile-marker.

High and low kill locations—The mean road-kills per mile were calculated for each highway and rounded to the nearest whole number. We generated 800m (0.5 mile) radius buffers around each mile-marker sampling site and we categorized each highway segment within the buffer as a 'high kill' or 'low kill' zone. We did this by comparing the total number of UVCs associated with a segment to the mean number of UVCs per mile for the same stretch of road for each of the five highways in the study area. If the summed number of UVCs associated with a single mile-marker segment was higher than the average calculated per mile for the same highway, that mile-marker segment was considered a 'high kill' zone. Similarly, if the summed number of UVCs within a mile-marker segment was lower than the average for that highway, the mile-marker segment was defined as a 'low kill' zone. Each spatially accurate UVC location was classified as a high kill or low kill zone according to which mile-marker segment it fell within. For example, a mile-marker segment with greater than or equal to 2 road-kills on Highway 40 in Kananaskis was a high kill zone, while a segment with less than 2 road-kills was a low kill zone.

Variables and Models

Site-specific variables—We measured site-specific variables at 499 sites from the spatially accurate data and 120 sites from the mile-marker dataset between April 2003 and July 2005. Only 499 UVC locations were used, because 47 UVC reports from Kootenay Highway 93 South were excluded. The excluded reports occurred prior to the clearing of roadside vegetation along a 24 km stretch of the Kootenay Highway 93 South. Using a differentially-correctable GPS unit to locate each sampling site, we measured 14 variables to be used as possible factors explaining UVC occurrence (Table 23). A range finder (Yardage Pro® 1000, Bushnell® Denver, CO) measured distance to nearest vegetative cover, and the inline and angular visibility measurements. Vegetative cover, habitat, topography, and slope were all estimated visually. Field visibility variables estimated the extent to which a motorist could see ungulates on the highway right-of-way, or conversely, how far away an oncoming vehicle could be seen from the side of the highway. Field visibility was measured via a rangefinder as the distance that an observer, standing at one of three positions (edge of the pavement, 5m from pavement edge, or 10m from pavement edge), lost sight of a passing vehicle. This measurement represents the distance that an approaching driver might be able to see an animal from the road. Since in most cases it could not be determined from what side a vehicle struck an animal, or in which direction the vehicle was traveling, four visibility measurements were taken at each position (two facing each direction of traffic on both sides of the highway). These four measurements were averaged to provide mean values estimating visibility at the edge of the road, 5m away from the edge of the road, and 10m from the edge of the road. These positions are defined as 'in-line visibility', 'angular visibility 1', and 'angular visibility 2' respectively, as referred to in Table 23.

Spatial and elevation data were collected along each highway approximately every 25m, by driving at 50km/hr and recording a GPS location every second. Elevation

was obtained on-site from a GPS unit for the spatially accurate data locations, whereas elevation for the mile-marker points was extracted from the GPS-created highway layer.

GIS derived variables—Measurements for most variables were obtained in the field, some were obtained using ArcView 3.3 GIS.[77] Distance from each sampling site to landscape features (Table 23) was calculated using GIS. We generated 800m (0.5 mile) radius buffers around each spatially accurate and mile-marker sampling site, and laid various landscape feature layers over the buffers to calculate the area or length of each within each buffer. The road network was used to calculate the length of each highway segment within each buffer to measure curvature of the highway (Table 23).

Data Analysis

Cluster analysis—We tested whether the spatially accurate UVCs were distributed randomly by comparing the spatial pattern of collisions with that expected by chance, in which case the likelihood of collisions for each road section would show a Poisson distribution.[32] For each of the four watersheds, we divided the highways into 100m segments and recorded presence (1) or absence (0) of the observed points in each segment. We used a Kolmogorov-Smirnoff one-sample test to determine whether the empirical distribution differed from a Poisson distribution. We also used a χ^2 test based on overall highway length to determine if an obvious UVC aggregation was significant along the cleared section or low valley bottom of Kootenay Highway 93 South. Finally we determined the aggregation, (i.e. whether the kills were evenly spread along the highway) of UVCs within each highway, by determining the percentage of mile-markers associated with a UVC location.

We used univariate analyses to identify which of the continuous variables (unpaired t-tests) and categorical variables (χ^2 contingency tests), significantly ($p<0.05$) differed between high and low kill sites within the spatially accurate and mile-marker datasets. The significance of each differentiated class within the categorical variables was evaluated using Bailey's confidence intervals.[48]

We used logistic regression analyses to identify which of the significant parameters best predicted the likelihood of UVC occurrence within the spatially accurate and mile-marker datasets.[123] We used stepwise (backward) regression procedures to remove variables from the equation until the ensuing new model was not significantly more informative than the previous one. We used the log-likelihood ratio test[123] to determine the ability of each model to discriminate between high and low kill zones based on location attributes. Significance of explanatory variable coefficients was based on the χ^2 of the Wald statistic.[123] Standardized estimate coefficients were calculated by multiplying logistic regression coefficients (B) by the standard deviation of the respective variables. With this, we assessed the relative importance of the explanatory variables within the model. Odds ratios were examined to assess the contribution that a unit increase in the predictor variable made to the probability of a UVC occurring.[228] Hosmer-Lemeshow goodness-of-fit test statistics were included to see how well the model predicts the dependent variable. We also included the cross-validation classification

Table 23: Definition and description of variables used

Variable Name	Definition
Field variables	
Habitat class*	Dominant habitat within a 100m radius on both sides of the highway measured as open (O)-meadows, barren ground; water (W)-wetland, lake, stream; rock (R); deciduous forest (DF); coniferous forest (CF); open forest mix (OFM)
Topography*	Landscape scale terrain measured as flat (1), raised (2), buried-raised (3), buried (4), part buried (5), part raised (6)
Forest cover	Mean percentage (%) of continuous forest cover (trees >1m height) in a 100m transect line perpendicular to the highway, taken from both sides of the road
Shrub cover	Mean percentage (%) of shrub cover (trees and shrubs <1m high) in a 100m transect line perpendicular to the highway, taken from both sides of the road
Barren ground	Mean percentage (%) of area devoid of vegetation (rock, gravel, water, pavement etc.) in a 100m transect line perpendicular to the highway, taken from both sides of the road
Vegetative cover	Mean distance (m) to vegetative cover (trees and shrubs >1m high) taken from both sides of the road
Roadside slope	Mean slope (°) of the land 0-5m perpendicular to the pavement edge taken from both sides of the road
Verge slope	Mean slope (°) of the land 5-10m perpendicular to the pavement edge taken from both sides of the road
Adjacent land slope	Mean slope (°) of the land 10-30m perpendicular to the pavement edge taken from both sides of the road
Elevation	GPS height (m)
Road width	Distance (m) from one side of the highway pavement to the other
In line visibility-field*	Mean distance at which an observer standing at the pavement edge could no longer see passing vehicles taken from each direction on both sides of the highway
Angular visibility 1	Mean distance at which an observer standing 5m from the pavement edge could no longer see passing vehicles taken from each direction on both sides of the highway
Angular visibility 2	Mean distance at which an observer standing 10m from the pavement edge could no longer see passing vehicles taken from each direction on both sides of the highway
Distance to landscape features	
Drainage	Distance (m) to the nearest waterway (river, stream, or creek) which crossed the road
Human use	Distance (m) to the nearest human use feature along the highway
Barrier-guardrail	Distance (m) to the nearest Jersey barrier or guardrail
GIS generated buffer variables	
Road curvature	Length (m) of each highway segment within each buffer
Open water	Area (km^2) of open water within each buffer
Human use	Area (m^2) of human use features within each buffer
River length	The length (m) of all rivers within each buffer
Barrier length	The length (m) of all Jersey barriers and guard-rails in each buffer

* Variable measure obtained from field measurement

(1) flat   ———   (2) raised   ⌒   (3) buried-raised

(4) buried   ╲__╱   (5) part-buried   ╲__   (6) part-raised   ╱—
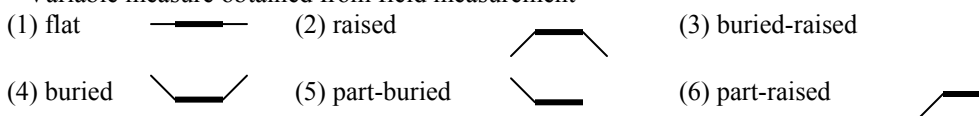
accuracies for each model generated from the two datasets. Each model was validated with 20% of the data not included in their development to determine their cross-validation classification accuracies.

Prior to performing the regression analysis, we tested potential explanatory variables for multicollinearity.[167] Where variables correlated (r>0.7), we removed one of the two variables from the analysis. Final models and variable coefficients with a p-value ≤0.1 were considered significant. We used the SPSS statistical package version 13.0 for all statistical analyses,[219] and Microsoft Excel and ArcView GIS 3.3[77] for all other analyses.

Findings and Results

Summary of Ungulate-Vehicle Collision Data

A total of 546 UVC observations were recorded between August 1997 and November 2003 on all highways in the study area. Deer (mule deer, white-tailed deer and unidentified deer) were most frequently involved in collisions and comprised 58% of the kills, followed by elk (27%), moose (7%) bighorn sheep (3%) and 'other ungulates' (including mountain goats, unknown species of ungulates – 5%).

The majority of UVCs occurred on the Trans-Canada Highway (TCH) east of Banff National Park in the province of Alberta (46%), followed by Highway 93 South in Kootenay National Park (22%), Highway 40 in Kananaskis Country (12%), the TCH in Yoho National Park (10%), and the TCH in Banff National Park (10%). Calculating the average number of kills per mile for each highway in the study area, showed that the majority of UVCs occurred on the TCH in the province of Alberta (13.6 kills/mile), followed by the TCH in Banff National Park (2.6 kills/mile), the TCH in Yoho National Park (2.1 kills/mile), Highway 40 in Kananaskis (2.1 kills/mile) and Highway 93 South in Kootenay National Park (1.8 kills/mile). These UVC rates followed traffic volume trends, which were highest on the TCH east of Banff National Park in the province of Alberta, followed by the TCH in Banff National Park, TCH in Yoho National Park, Highway 40 in Kananaskis Country, and Highway 93 South in Kootenay National Park.

Spatial Distribution of Road Kills

The accuracy of the location where site-related variables were measured for the spatially accurate locations was approximately ≤ 10m. The UVC distributions from the spatially accurate dataset differed significantly from random distributions along all five highways in the study area (Kolmogorov-Smirnov one-sample test: TCH-Bow River Valley, d = 0.715: Highway 93 South in Kootenay, d = 0.940; TCH-Yoho, d = 0.892; Highway 40 in Kananaskis, d = 0.874; all p<0.01). The distribution of UVCs on Highway 93 South in Kootenay showed a significant aggregated distribution where the highway traversed the low valley bottom with 60% of the kills occurring along a 24 km (23%) stretch of road ($\chi2$ = 63.9, p<0.0001). The TCH in Alberta had the majority of mile markers associated with a road-kill (89%), followed by the TCH in Banff National Park (86%), followed by Highway 40 (84%), followed by 93S in Kootenay National Park (61%), and the TCH in Yoho National Park (57%). Due to the non-random pattern and

aggregation of UVCs, we addressed specific questions as to which landscape and road-related factors contributed to the distribution of collisions in the study area.

Models

 Univariate tests—Table 24 shows the results of the univariate tests comparing high and low kill locations for each environmental variable contributing to the probability of UVCs in each dataset. Each dataset had variables in each group that were significant in detecting differences between UVC high and low kill zones , however only three vs. ten variables were significant in the mile marker dataset.

 Within the spatially accurate dataset, Table 24 shows that six of the field-based variables were significant: habitat class, topography, forest cover, cleared ground, adjacent land slope, and road width. Only two of the field variables (road width and topography) were significant from the mile-marker dataset. In both datasets, more UVCs occurred when the topography was flat and the roads were wide. In the spatially accurate dataset, more UVCs occurred than expected in open forest habitat and fewer UVCs occurred than expected in coniferous forest and rocky areas.

 Within the landscape features variables, distance to drainage and barrier-guardrail were significant (negatively correlated) in the spatially accurate dataset. More UVCs occurred than expected closer to drainages perpendicular to the roadway and closer to barriers-guardrails (including Jersey barriers). No distance to landscape features were significantly correlated to the low or high kill zones in the mile-marker dataset.

 Within the GIS-derived variables, area of open water showed a significant negative correlation to the dependent variable in the spatially accurate dataset, while only measure of barrier length gave a significant negative correlation in both datasets. Less open water and shorter lengths of barriers were associated with high kill zones.

 To reduce intercorrelation between the variables [251], we omitted the percentage forest cover from further analyses as it was highly correlated (r > 0.70) with percent cleared ground.

 Logistic regression analysis—Both models ranked differently in their ability to predict the observed likelihood for UVCs (Table 25). The variables used in each model could collectively be used to predict where a UVC would occur for the spatially accurate model (p < 0.0001) but not for the mile marker model (p = 0.584) as determined from the log likelihood ratio test. For the spatially accurate model, the Hosmer and Lemeshow statistic was higher than the mile-marker model. The predictive capabilities of the spatially accurate model correctly classified 81.8 %, while the mile-marker model correctly classified only 64.4% of the selected UVC data. Model validation accuracies were 76.9 % for the spatially accurate model and 63.3% for the mile-marker model. Type of habitat was the most important variable in explaining UVCs in the spatially accurate dataset. Ungulate-vehicle collisions were less likely to occur near open water, deciduous forest, closed coniferous forest, and open forest mix relative to open habitat. Kills were 2.7 times less likely to occur in water- dominated habitats (lakes, wetlands) relative to open habitat areas (dry meadows, clearings). Further, distance to drainage had a significant negative correlation with the occurrence of UVCs in the spatially accurate

Table 24: Univariate comparison of factors contributing to UVCs

Variable	Spatially accurate			Mile-marker		
	High	Low	p-value	High	Low	p-value
Field Variables						
Habitat			<0.0001			
Rock	2	11				
Coniferous forest	144	177				
Open forest mix	112	54				
Topography			<0.0001			0.0035
Flat	241	172		24	12	
Buried-raised	32	71				
Forest cover	46.7	53.3	0.0256			
Openness	47.3	41.6	0.0496			
Adjacent land slope	11.4	15.9	0.0059			
Road width	34.1	24.8	0.0001	19.51	15.2	0.0300
Distance to Landscape features						
Drainages	2389.9	3068.9	0.0003			
Barrier-guardrail	627.0	1052.2	0.0003			
GIS generated buffer variables						
Barrier length	272.7	353.2	0.0182	336.51	548.4	0.0036
Open water	49.2	109.8	0.0001			

This table shows comparison using a spatially accurate dataset (n = 499; 391 high and 108 low-density points) and mile-marker dataset (n = 120; 63 high and 57 low-density points). Mean values are shown for quantitative variables, and frequencies for each differentiated type are shown for categorical variables, along with their associated p-values. Only those values that were significant at p < 0.05 are displayed.

model. The distance to barrier-guardrail and the length of the barriers within the buffer both showed a negative correlation with UVCs. In the mile-marker model, barrier length showed a significant negative correlation with UVCs.

Table 25: **Logistic regression analyses for modeling factors contributing to UVCs**

Variable	Spatially accurate		Mile-marker	
Habitat				
Water	1-			
Coniferous forest	4-			
Deciduous forest	5-			
Open forest mix	2-			
Distance to drainage	3-			
Barrier-guardrail	N/A+			
Road width	N/A+			
Barrier length	N/A-		1-	
Open water	N/A-			
Hosmer and Lemeshow test	0.764		0.512	
Model development & validation accuracies (%)	81.8	76.9	64.4	63.3

In Table 25, results from the logistic regression analyses for modeling the factors contributing to UVCs using two datasets are shown. They include a spatially accurate dataset (n = 499 locations; 391 high and 108 low-density points) and a mile-marker dataset (n = 120; 63 high and 57 low-density points). Also shown are their associated ranking of significant (p<0.10) standardized estimate coefficients and their sign. Numbers indicate the rank of importance of the variable. The sign indicates the influence the variable or variable level has on the probability of a road kill occurring [(-) negative correlation or (+) positive correlation]. Hosmer and Lemeshow goodness of fit test and overall cross-validation accuracies are included; the term N/A means that the standard deviation in the logistic regression output was equal to zero.

Interpretation, Appraisal, and Applications

Summary of UVC data

For our analysis, we used the largest database of its kind with spatially accurate information on the occurrence and specific carcass location of WVCs. The traffic mortality database is also unique in that it spans a relatively short time-period (1999-2005), whereas other databases, regardless of their spatial accuracy, often contain road-kill information from a decade or more. The short time span used in this analysis is important because over long time-periods, environmental variables may change (e.g., roadside vegetation and motorist visibility, habitat quality), as can road-related variables (guardrail and Jersey barrier installation, road widening and improvements, lighting), thus confounding analysis and resulting in spurious results.

Previous explanations for the clustering of WVCs, included parameters such as animal distribution, abundance, dispersal, and road-related factors including local topography, vegetation, vehicle speed, and fence location or type.[190,4,47] Few studies have demonstrated that WVCs are correlated with traffic volume.[160,4,47,124] The majority of WVCs in our analysis took place in the provincial section of the TCH followed by Highway 93 South in Kootenay National Park. However, when the road-kill frequencies were standardized by highway length in our study area, we found that the rate of road-kill was positively correlated with traffic volume.

Factors other than traffic volume alone may influence collision rates, but these aspects may be masked if a more detailed and rigorous analysis is not conducted. Previous research in the same Canadian study area found that elk-vehicle collision rates were significantly different between road types and declined over time on the TCH in Banff and Yoho National Parks, and Highway 93 South[53]. In the above analysis, when the effects of traffic volume and elk abundance on elk-vehicle collision rates were isolated, the latter was particularly important.[53] Significant interactions indicated that road type influenced these effects and greater elk abundance led to increased elk-vehicle collisions. For this analysis in this report we did not include elk abundance as an independent variable because the quality of information for site-specific locations (i.e., UVCs) would not lend itself well to a rigorous statistical analysis. Of the five highways included in our study, the relative abundance of ungulates is highest in the provincial section of the TCH and Kootenay River Valley along Highway 93 South. The other highways (TCH-Banff, TCH-Yoho, Highway 40) are situated at higher elevations and have lower ungulate densities. Few studies investigating factors influencing WVCs have included data on animal abundance.[20,190,53]

Models of UVCs

Spatial distribution and aggregation—The spatial distribution of UVCs on all five highways in the study area was not random. The most notable aggregation was along the 24 km stretch of highway on 93 South. This segment of highway bisects key ungulate ranges in the valley bottoms of the montane region, with elevation less than 1240 m.[188]

Several environmental and road-related variables had high explanatory power in describing UVCs on all highways, and these variables were dependent on the spatial accuracy of the dataset. Results of the univariate analysis demonstrated that the spatially accurate dataset had substantially more significant variables (n = 10 variables) explaining the factors associated with UVCs than the mile-marker dataset (n = 3 variables).

Predictive ability of data sets—Univariate tests and Logistic regression analysis

Univariate Tests

Among the field-based variables, only two were identified in the mile-marker dataset as being significant in detecting differences between UVC high and low kill zones. The same variables were also identified among the six significant variables in the spatially accurate dataset. Two of the variables from the distance to landscape features and GIS-generated buffer variables were significant from the spatially accurate dataset, whereas the mile-marker dataset had none.

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Univariate tests are often used as a preliminary step to identify variables (or combinations of them) that are most likely good predictors of responses to include in an a priori logistic regression analysis.[123] The results of the univariate tests of significance provide an interesting comparison of how well each dataset is able to describe the relationship between predictor variables and the location of UVCs. Of the 22 variables used in the initial univariate test to identify variables that differed significantly between high and low UVC kill zones, ten (roughly half) of the spatially accurate variables compared to only three (<10%) of the mile-marker variables were statistically significant.

Logistic regression analysis

Results of the logistic regression analysis to predict the likelihood of UVCs for the two datasets analyzed in this study showed the spatially accurate model was statistically significant, however, the mile-marker model was not. Further, both of the models differed considerably in how well they predicted the likelihood of UVCs. Strong support of the predictive ability of the spatially accurate model compared to the mile-marker model was found with the higher spatially accurate cross-validation scores. These results provide overwhelming evidence of the accuracy and utility of spatially accurate data as opposed to using mile marker data when investigating factors that are likely to explain accidents.

Factors that explain collisions—Our spatially accurate model indicated that adjacent habitat type was the most important variable in explaining UVCs. The proximity to open habitat increased the likelihood of UVCs as opposed to habitats characterized by open water, deciduous forest, closed coniferous forest, and open forest mix. Gunther et al.[109] reported that elk were involved in accidents significantly more often than expected in non-forested cover types. Many deer-vehicle accidents in Pennsylvania were concentrated around woodland-field interfaces in predominantly open habitat.[15] On the other hand, some studies have not found this association between habitat type and UVCs.[4,25] Wildlife tends to be associated with specific habitats that provide resources and environmental conditions that promote occupancy and survival.[176] Thus, the spatial distribution of habitat types adjacent to or bisected by a highway transportation corridor would likely influence the extent, severity, and locations of vehicle collisions with wildlife.

Landscape variables other than habitat and topography may also be important attributes determining UVCs. For example, distance to nearest drainage was significant and negatively correlated with the occurrence of UVCs in the spatially accurate model. Ungulates had a greater tendency to be involved in traffic accidents close to drainages systems. Drainage systems are known travel routes for wildlife, particularly in narrow glacial valleys such as Banff's Bow Valley.[51] Furthermore, research has shown that topography, particularly road alignment with major drainages, strongly influences the movement of ungulates toward roadways and across them.[20,45,159,86]

The proximity to potential barriers such as Jersey barriers and guardrails was an important predictor of UVCs in the study area. The same result was found when measuring the length of Jersey barrier or guardrail within the 800m buffer in high and low UVC kill zones. UVCs were found to occur closer to barriers such as jersey barriers and guardrails, which may be because animals are funneled to the ends of the barriers and

cross the highway at this point. Furthermore, fewer animals were killed when the length of barriers within the 800m buffer decreased. These results suggest that the barrier is obstructing animal movement and funneling animals to barrier ends, or particular features in the landscape associated with barriers such as lakes and steep topography are deterring animals from approaching the highway at these locations. Barnum [14] found that animals crossed more frequently at culverts, bridges, and at-grade crossings with no guardrail or median barrier. The only study modeling AVCs that included guardrails in the analysis also found that animals tended to avoid highway sections with these potential barriers, i.e. collisions were less likely to occur where barriers were present.[158]

The results have important ecological implications as they suggest that median barriers and guardrails may obstruct animal movement across highways. Further, the results have important management implications because state transportation agencies are constructing highway median barriers with virtually no information on how they affect wildlife movement and mortality. Despite these potential impacts, the 2003 AASHTO Roadside Design Guide does not address the impact of median barrier installation. Resource managers and transportation biologists have identified this as a severe shortcoming that needs immediate attention. A recent Transportation Research Board report highlighted the urgent need to better understand how wildlife respond to and are potentially impacted by highway barriers.[232]

Spatial accuracy and interpretation of results—In the mile-marker dataset, few landscape variables were significant. For example, level or gentle topography due to flat terrain is bisected by the TCH in the province of Alberta. Further, road width was a significant explanatory variable due to the width and number of lanes of traffic on the TCH in the province of Alberta. Both of these variables are not as dependent on spatial accuracy, because they were broad-scale measurements with low variability occurring on large sections of the highway.

None of the distance to feature variables showed significance in the mile-marker dataset. These types of variables are strongly dependent on spatial accuracy of reporting UVCs. For example, if a UVC location has an error up to 800m this will be evident in the measurement of these variables.

The GIS-generated buffer variables could be used to measure factors associated with UVCs in a mile-marker dataset.[158] The buffer encompasses the entire area in which the UVCs would have occurred, thus the factors associated with that road-kill are incorporated into the measurement of the variables. Barrier length was a significant explanatory variable in both datasets and area of open water was marginally significant in the mile-marker dataset. These variables would have to be a broad-scale landscape feature such as the area of a feature within the entire buffer.

Dataset comparison—The primary result of this analysis was that a UVC model developed with spatially accurate location data had high predictive power in identifying factors that may contribute to collisions. Perhaps more noteworthy from this exercise was the vast difference in predictive ability between the models developed with spatially accurate data, and the less accurate data obtained from referencing UVCs to a mile-marker system. This lends strong support to a categorical distinction between high kill vs.

low kill UVC zones (or where they are less likely to occur) when modeling is performed with spatially accurate UVC data.

Modeling animal–vehicle collisions has been carried out at a range of spatial scales, from local to state and nation wide analyses.[124,183,158,206,192] Previous studies have used readily available data (carcass or collision statistics) to identify variables that influence the risk of animal–vehicle collisions, and have recommended measures to reduce the number of fatalities. These studies have largely relied on referencing collision data several ways: (1) accepting and using location data (point data) or highway segments with animal–vehicle collisions ('hotspots') without knowledge of the inherent spatial error,[20,15,89,25,208] (2) referencing to a highway mile-marker system,[124] (3) referencing to a 0.1-mile-marker (or 0.1-km) system,[190,158,206,125] or (4) using spatially accurate UTM locations (< 10m error) obtained by a GPS unit at the location of accident.[53,192,193]

The above review of published studies illustrates that many studies that modeled animal–vehicle collisions typically have used data with a significant amount of spatial error, introduced by relying on a mile-marker system, or an equally flawed approach of not being able to verify the degree of spatial error associated with the collision data. One study that rigorously measured the reporting error in the Canadian Rocky Mountain parks found it was on average 516 ± 808m, and ranged from 332 ± 446m to 618 ± 993m.[53] The average distance reporting error of the Royal Canadian Mounted Police (highway patrol) animal–vehicle collision records in the same study area was 2154 ± 1620m (n = 26 records).

Plotting animal–vehicle collisions on maps using grid coordinates may not improve spatial accuracy in reporting. In the above study, the average distance reporting error associated with road-kill records (based on occurrence reports and mortality cards from the mountain national parks) was 969 ± 1322m.[53] The work we present here is the first to our knowledge to test the value of spatially flawed data by comparing model performance results with a spatially accurate dataset. Besides learning about the parameters that contribute to UVCs in our study area, we discovered that spatially accurate data does make a difference in the ability of models to provide not just statistically significant results, but more importantly, biologically meaningful results for transportation and resource managers responsible for reducing UVCs and improving motorist safety. Modeling collision-related parameters with spatially inaccurate data will almost certainly lead to spurious results at best, and thus fail to provide properly directed or applied mitigation of wildlife related traffic accidents.

The results have important implications for transportation agencies that may be analyzing data referenced to a mile-marker system and is spatially inaccurate. These implications are equally important for statewide analyses or even smaller districts. Spatially inaccurate data would be suitable for coarse-scale analysis to identify UVC hotspots, but for fine-scale needs (project or district level), greater accuracy in data will be essential for a rigorous analysis and development of sound mitigation recommendations.

A nationwide standard for the recording of animal–vehicle collisions would not only stimulate transportation departments and other organizations to collect more spatially accurate road-kill data, but it would also allow for better integration and

analyses of the data. Some transportation agencies are also beginning to use Personal Data Assistants (PDAs) in combination with a GPS for routine highway maintenance activities (eg, Washington State).[126] These two initiatives can help agencies collect more spatially accurate and standardized data that will eventually lead to more informed analyses for transportation decision-making.

Landscape vs. road-related variables— Wildlife tend to be associated with specific habitats, terrain, and adjacent land use types. Thus, landscape spatial patterns would be expected to play an important role in determining road-kill locations and rates.[95] Explanatory factors of wildlife road-kills vary widely between species, often explained by habitat preferences and species abundance patterns.[52,192] Increasingly, studies are beginning to look at the types of variables that explain wildlife–vehicle collisions, whether they are associated with landscape and habitat characteristics, or physical parameters related to the road environment.[208,206] In our study, 22 variables were evaluated, 11 associated with landscape or habitat attributes and nine associated with the road environment. In the univariate analysis, ten variables were significant in explaining UVCs; eight were related to landscape, while only two were associated with the road environment. In the logistic regression analysis, three explanatory variables were significant, two were landscape-based and one was from the road environment. These results demonstrate the importance of ecological attributes in our analysis, and suggest analyses that fail to adequately consider ecological variables in UVC analyses along with road-related variables, will more often than not provide spurious results.

HOTSPOTS MODELING (3.3)

Lead:

Anthony P. Clevenger, Amanda Hardy, Kari Gunson

Abstract

Transportation departments need to be able to identify where particular wildlife species and communities are susceptible to high road-kill rates along roads in order to effectively reduce road impacts on wildlife and to increase motorist safety. Research on animal─vehicle collisions (WVC) has demonstrated that they do not occur randomly but are spatially clustered. In this report, we investigated WVC hotspot identification techniques, taking into account different scales of application and transportation management concerns. Wildlife-vehicle collisions datasets were obtained from two locations in North America with varying wildlife communities, landscapes, and transport planning issues. We then used the Linear Nearest Neighbor Analysis Index as an initial step to measure whether the data points were random, and three clustering techniques (Ripley's K-statistic of road-kills, nearest-neighbor measurements, and density measures) that can be used more formally to identify WVC hotspots in a variety of landscapes. We conclude by synthesizing the results and their applications, demonstrating how this information can be used to aid transportation management decisions, and suggesting guidelines for the use, analysis, and applications of WVC data for transportation mitigation planning practices.

Introduction

Animal─vehicle collisions (WVC) are a significant problem in North America, particularly in rural or suburban areas where people rank them as a major safety concern. A recent survey of motorists in Montana, Idaho, and Wyoming ranked animals on the roadway as one of the top three safety issues.[82] A survey of northern California and rural Oregon stakeholders reported similar concerns. In much of the western United States, road networks are extensive and motor vehicle use has sharply increased as wild lands are progressively developed and suburbanized.[21,110] The human population with its associated infrastructure expansion that many states and municipalities are experiencing, in association with increasing wildlife populations in some areas, have led to greater safety concern and need to develop effective countermeasures to mitigate WVCs. In 2002, it was estimated that there were more than 1.5 million WVCs resulting in 150 fatalities and $1.1 billion dollars in vehicle damage.[116]

Studies of WVCs have demonstrated that they are not random occurrences but are spatially clustered.[190,124,51,134] However, there are few studies that specifically address the nature of WVC hotspots or their use and application in transportation planning.[148,136] These studies have been spatially explicit and utilized one method of determining hotspot locations. Many of the studies characterizing WVCs have appeared in scientific and management-focused

journals, and often include different conclusions or recommendations for managers to consider in designing wildlife-friendly highways.[190,124,183,158] However, lacking are best management practices for identifying WVC hotspots based on current knowledge and technology to help guide planning and decision-making.

Because WVCs represent a distribution of points, clustering techniques can be used to identify hotspots. Simple plotting of WVC location points can be done in a variety of geographic information system (GIS) formats, for example ArcView® or ArcGIS®,[77,78] currently being used by many transportation agencies. Simple plotting does not require statistical algorithms or metrics, but is based on visual groupings of road-kill clusters and decision-based rules of defining hotspots. Clustering of WVCs has been correlated to animal distributions, abundances, dispersal habits, and road-related factors including local topography, vegetation, vehicle speed, and fence location or type.[190,4,47,51]

In this report we investigate various WVC hotspot identification clustering techniques that can be used in a variety of landscapes, taking into account different scales of application and transportation management concerns (e.g., motorist safety, endangered species management). We obtained WVC datasets from two locations in North America with varying wildlife communities, landscapes, and transportation planning issues. We demonstrate how this information can be used to identify WVC hotspots at different scales of application (from project level to state level analysis). The model based clustering techniques that we demonstrate included a Linear Nearest Neighbor Analysis used initially to measure if the WVC locations were random and then Ripley's K-statistic, Nearest-Neighbor Measurements, and Density Measures to identify hotspots. We provide an overview of software applications that facilitate these types of analyses. The information presented in this report is intended to advance our understanding of the considerations that must be taken into account when analyzing WVC datasets of varying qualities and scales. Results from this effort should help agencies hone their WVC data collection and analytical techniques in order to yield more accurate and useful information that can be used to mitigate negative impacts related to wildlife-transportation conflicts. The work complements the growing body of research on mitigating road impacts for wildlife and improving highway safety. Lastly, it provides practitioners and managers with methods that can be quickly applied to available information and ultimately streamline the delivery of transportation projects in areas where WVCs are a major concern to agencies and stakeholders.

Research Approach: Methods and Data

Mapping Techniques

The objective of this research was to investigate different mapping techniques that can be used to identify WVC hotspots. The techniques can be categorized as: 1) Simple graphic, visual mapping exercises, and 2) Modeling of analytical techniques used to identify non-random clusters or aggregations of WVCs. The simple plotting of WVCs can be done in a variety of GIS formats, for

example ArcView® or ArcGIS®, currently being used by many transportation agencies. Simple plotting does not require statistical algorithms or metrics, but is based on visual groupings of road-kill clusters and decision-based rules of defining hotspots. Modeling WVCs using clustering mapping techniques is a more complicated matter. We evaluated the mapping techniques in the context of different scales of application (project level to state level analysis) and transportation management concerns (e.g., motorist safety, endangered species management). We describe different mapping techniques using <u>one</u> dataset, WVCs in the Canadian Rocky Mountains, to demonstrate how this readily available information can be used by transportation agencies to identify collision hotspots at different scales of application. We then selected one clustering technique (Crimestat) and ran hotspot analysis using <u>two</u> different datasets: Ungulate vehicle collision (WVC) carcass data from Canadian Rocky Mountains and Caltrans deer-carcass data (DVC) data from Northern California. We then described the hotspot patterns/configurations, and examined how they may differ by species and the two landscape types.

Study area

Canadian Rocky Mountains

This study took place in the central Canadian Rocky Mountains in western Alberta approximately 100 km west of Calgary (Figure 6). The area encompasses the Bow River watershed and includes mountain landscapes in Banff National Park and adjacent Alberta Provincial lands in Kananaskis Country. Topography is mountainous, elevations range from 1,300 m to over 3,400 m, and valley floor

Table 26: Characteristics of the major highways in the study area

Highway	Watershed	Province	Road length (Km)	Traffic volume (ADT[1])	Posted vehicle speed (Km/hr)
Trans-Canada Highway	Bow River	Alberta, east of Banff National Park	37	16,960	110
Trans-Canada Highway	Bow River	Banff National Park, Alberta	33	8000	90
Trans-Canada Highway	Kicking Horse River	Yoho National Park, British Columbia	44	4600	90
Highway 93 South	Kootenay River	Kootenay National Park, British Columbia	101	2000	90
Highway 40	Kananaskis River	Alberta	50	3075[2]	90

[1] 2005 annual average daily traffic volume. Data from Parks Canada Agency, Banff National Park and Alberta Transportation, Edmonton, Alberta.

[2] 1999 summer average daily traffic volume. Data from Alberta Transportation, Edmonton, Alberta.

width varies from 2-5 km. Highways in the study area traverse montane and subalpine ecoregions through four major watersheds in the region. Table 26

describes the location and general characteristics of the five segments of highways that were included in this study. The roads in this study traversed montane and subalpine ecoregions. Vegetation consisted of open forests dominated by Douglas fir (*Pseudotsuga menziesii)*, white spruce (*Picea glauca),* lodgepole pine (*Pinus contorta)*, Englemann spruce (*P. englemannii),* aspen (*Populus tremuloides)* and natural grasslands.

Northern California

This study took place in Sierra County, California in the Sierra Nevada Mountains (Figure 7). California State Highway (SH) 89 runs along the east side of the Sierra Nevada Mountains from the towns of Truckee to Sierraville. The California Department of Transportation (hereafter referred to as Caltrans) has consistently collected deer carcass data on this highway from June 1979 to October 2005. We used 849 deer carcass locations collected along 33 miles of Highway (SH) 89. The data were collected by maintenance supervisors and varies in spatial accuracy from the closest 1.0-mile, 0.1-mile, and 0.001-mile. The highway is a two-lane undivided highway with an Annual Average Daily Traffic Volume (AADTV) of 2250, peaking at 3300 in the summer months. Elevation ranged from 6150 feet (~ 1875 m) surrounding the southern most section of highway (mile 11.0) to 5081 feet (~ 1549 m) in the northern section. The dominant vegetation is ponderosa pine *(Pinus ponderosa*) bitterbrush (*Purshia tridentata)* and sagebrush *(Artemisia tridentata)*. The area receives relatively less precipitation than in the west because it is located in a rainshadow. Winter months can have up to 2-3 feet (~ 0.6-0.9 m)of snowfall. (Sandy Jacobson, personal communication). The SH 89 bisects an important migration route for the Loyalton-Truckee mule deer (*Odocoileus hemionus*) herd, which travels across the highway during upslope and downslope seasonal migrations. The highway also bisects the home ranges of numerous resident deer and is important for forest carnivores and amphibians.

Findings and Results

Hotspot Identification and Patterns for One Species and Landscape

Simple Graphic Techniques, One Dataset

Visual analysis and observation of WVC patterns

We obtained the Universe Transverse Mercator (UTM) coordinates using a geographic positioning system (GPS) unit for over 500 spatially accurate carcass locations (< 3m error) of WVCs between 1997 and 2004 in the Canadian Rocky Mountains. We used the UTM Nad 83 location to plot all of the WVC data within ArcGIS 9.0 on the highway network. We derived the hillshade raster dataset from the digital elevation model (DEM: Parks Canada, GIS data management) and used this as a backdrop layer for visual interpretation.
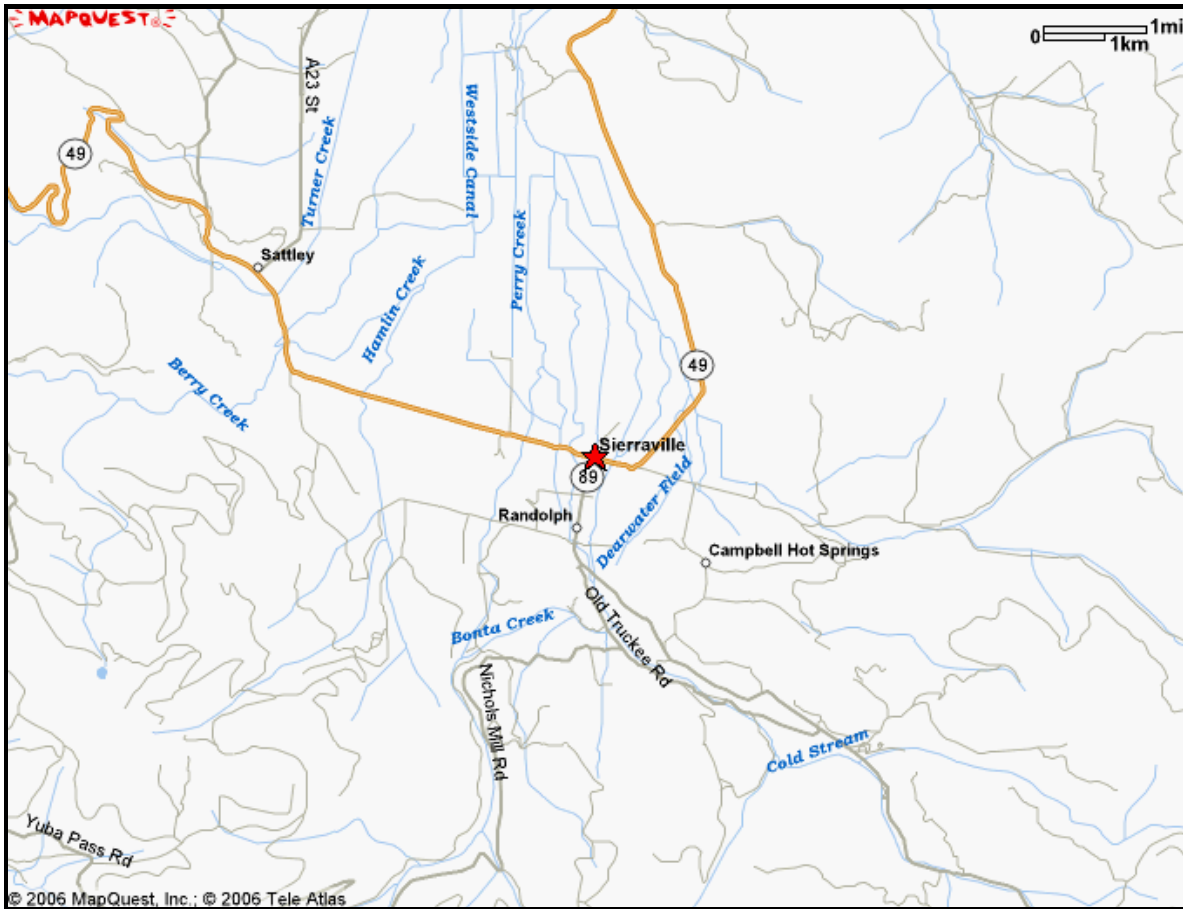
Figure 7: Location of study area in northern California in Sierra County, California

A total of 546 WVC observations were recorded between August 1997 and November 2003 on all five highways in the study area. Deer comprised 58% of the kills, elk 27%, moose 7%, Rocky Mountain bighorn sheep 3%) and other ungulate species (5%). The majority of WVCs occurred on the TCH east of Banff National Park in the province of Alberta (46%), followed by Highway 93 South in Kootenay National Park (22%), Highway 40 in Kananaskis Country (12%), the TCH in Yoho National Park (10%), and the TCH in Banff National Park (10%).

A simple visual analysis of the WVC locations is shown in Figure 8. It became obvious that a simple plotting of all WVC locations along highways did not clearly identify key areas where WVCs occurred or areas where higher than average densities of collisions – at least in this type of mountainous landscape that characterized the study area. Simple plotting resulted in collision points being tightly packed together, in some cases directly overlapping with neighboring WVC carcass locations, thus making it difficult to identify where the real high-risk collision areas occurred. The use of a DEM and/or land cover map overlay does provide readily available information on the juxtaposition of WVCs to terrain features (lowlands, lakes, steep terrain, vegetation cover types). A visual analysis can provide some cursory conclusions about why and where WVCs tend

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to occur most. However, a more rigorous spatial analysis can be carried out to summarize or test statistically the 'why and where' questions.

Terrain and habitat are often key factors influencing where WVCs occur (Clevenger et al.; Section 3.2 this report).[52,15,158,25] Type of terrain and the nature of the landscape mosaic would be expected to influence WVC hotspot clustering patterns. For example, landscapes with homogeneous cover types and with little topographic relief (i.e., flat terrain) would likely result in a more random pattern of movement across a highway, and thus a more dispersed pattern of collision locations on a given stretch of highway. Contrarily, a highly heterogeneous landscape with dissected topography is more likely to result in more clearly defined crossing locations and collision hotspots. The factors that contribute to these collisions will be different in both landscapes. More simplistic models with fewer explanatory variables could possibly be used to characterize the level, more homogeneous landscape, but more complex models with numerous variables may work better in the more diverse landscape. Landscape diversity may well influence the causes and spatial distribution of WVCs.

Analytical Techniques, One Dataset

Linear nearest neighbor analysis

All WVCs were plotted for each highway on the highway network layer in ArcGIS 9.0. We used the Hawth's Analysis Tools[24] extension to generate the same number of "random WVCs" as there were actually observed on each highway. We then used a first order linear nearest neighbor index (NNI) to evaluate if the distribution of the observed WVCs in each region of the Canadian Rocky Mountains differed from a random distribution. The index is a ratio between the mean nearest distance to each WVC (d(nn)) and the mean nearest distance that would be expected by chance (d(ran)). Equation shown below. We used Hawth's Analysis Tools to calculate d(nn) and d(ran).

$$NNI = d(nn)/d(ran)$$

If the observed mean distance is smaller than the random mean distance then the WVCs occur closer together than expected by chance and NNI<1, where NNI is the Nearest Neighbor Index. Once tabulated, the data were imported into Microsoft Excel where we calculated a Z-statistic, adapted from Clark and Evans,[50] to test whether there was a significant difference between random and observed distances.

The nearest neighbor index showed clustering (NNI<1) for all highway regions except for the TCH in Yoho, which showed evidence of dispersion (Table 27). The Z-statistic was significant (p < 0.05) for the TCH in Alberta and marginally significant (p = 0.066) for Highway 93 South.
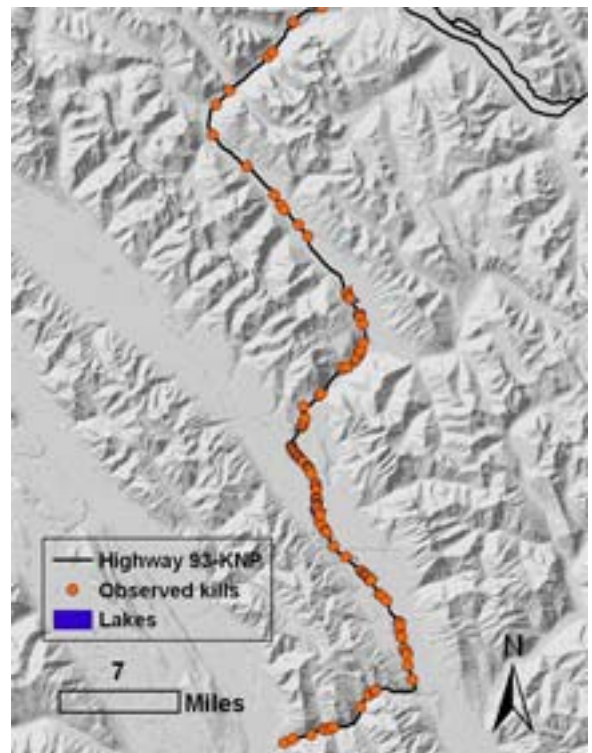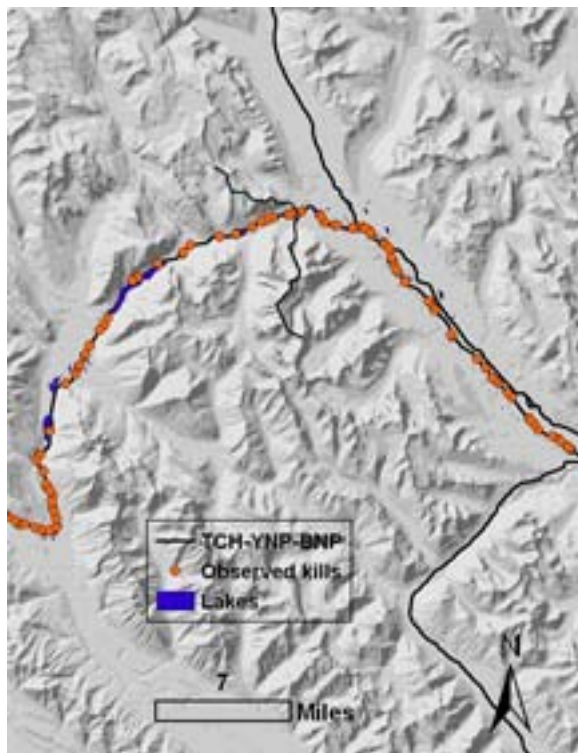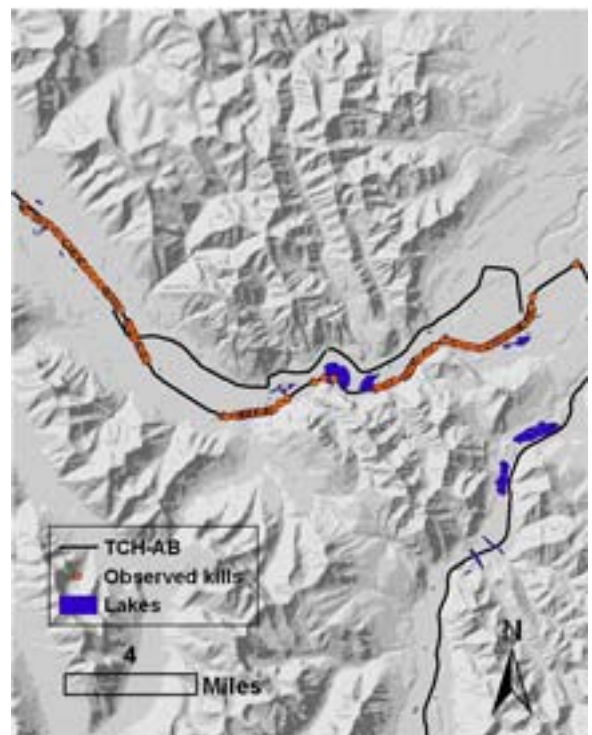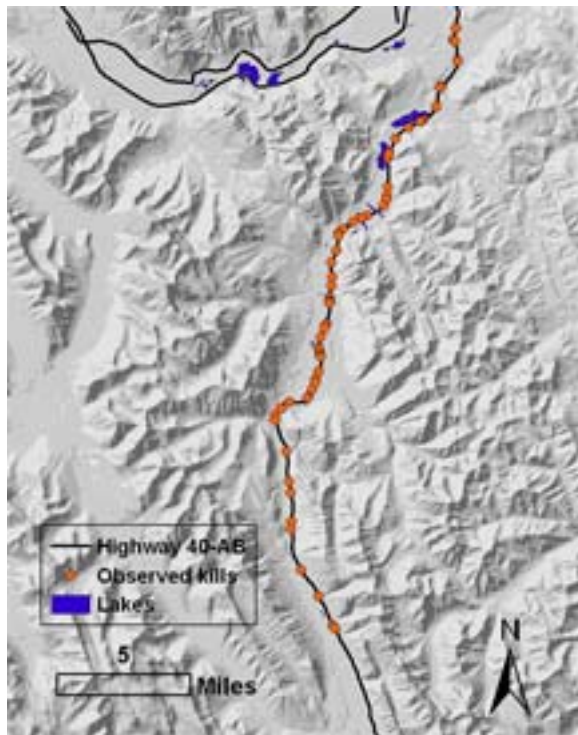
Figure 8: Spatially accurate locations of WVC locations on each road in each of the watersheds

Table 27: Descriptive statistics of the Crimestat® clusters and high kill zone aggregations

Region	No. Clusters	Mean cluster length ± SD (km)	No. high kill zones	Mean high kill zone aggregation length ± SD (km)	Cluster overlap index (cluster length$_{\text{high kill zone}}$/cluster length)
TCH-YNP	6	1.00 ± 0.32	7	2.80 ± 1.33	1.00
TCH-BNP	6	0.92 ± 0.38	11	4.40 ± 3.98	0.64
TCH-AB	7	1.32 ± 0.14	12	3.84 ± 1.63	0.90
40-Kan	6	0.96 ± 0.42	13	4.16 ± 3.29	0.85
93-KNP	17	0.86 ± 0.39	19	3.49 ± 2.34	0.56

The NNI used in this analysis is only an indicator of first order spatial randomness; a K-order nearest neighbor distance (e.g., second or third order) would likely better describe the overall spatial distribution of WVCs.[145] Sample sizes were small on the TCH in Yoho and Banff, and Highway 40 in Alberta (< 100), making it difficult to describe overall spatial distributions of WVCs in these regions.

The linear NNI is a quick and easy statistical test of spatial distribution of WVCs to determine initially whether collisions are distributed randomly across a stretch of highway or larger highway network (e.g., a DOT district or region). If the test indicates that there is clustering of WVCs (NNI < 1.0), then the subsequent step would be to identify where the WVC clusters occur using a GIS-based spatial analysis. Some spatial analysis techniques include cluster analyses using a GIS-based nearest-neighbor index,[25] mapping road-kill densities using a 'moving window' analysis,[213] or a road segment approach to mapping road-kill densities.[89,136] One approach that has great promise and is user-friendly is the Crimestat® program developed by Levine.[146]

Cluster analysis – nearest neighbor hierarchical technique

We used Crimestat® version III[146] to determine the location of high kill zones or WVC hotspots within each of the five highways of the Canadian Rocky Mountains study area. This is a nearest neighbor hierarchical technique, which identified a series of points that are spatially close based on a predefined set of criteria.[146] The clustering is repeated until either all points (WVCs) are grouped into a single cluster or else the clustering criterion fails. We used a fixed threshold distance for the search radius to determine the inclusion of an WVC in a cluster. We used 800 m as the threshold distance, because 800m was the same radius used in the mile-marker density analysis (see Density Measures below). We used the mean number of WVCs per mile for each highway region as the criteria for the minimum number of points required to define a cluster. This was the same criterion that determined whether a one-mile buffer was a high or low kill zone (see Density Measures below). A convex hull was used as the cluster output which draws a polygon around the WVCs in the cluster. Since the road-kills occurred in a one dimensional plane, a line was drawn from the two outermost points along the road within the convex hull for visual display and to calculate the length of each WVC cluster.

A total of 42 WVC clusters were produced using the nearest neighbor Crimestat® analysis and comprised 41 km of highway in the study area (Figure 9). Compared to the simple visual analysis of WVCs, the Crimestat® modeling technique effectively reduced

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the blurring of information associated with numerous WVCs on long stretches of highway. As mentioned earlier, simple plotting of WVC locations tends to result in tight grouping of collision points that often overlap with other WVC locations, making it a challenge to identify where high-risk collisions areas actually occur. The location and number of WVC hotspots generated by the Crimestat® technique are clearly defined and can be identified with associated landscape or road-related features in each highway area.

Ripley's K analysis

Ripley's K-statistic describes the dispersion of data over a range of spatial scales.[200,67] We calculated Ripley's K-statistic for all WVC mortalities in each region of the Canadian Rocky Mountains. We used the K-statistic as defined by Levine,[145] but modified for points distributed in one dimension (i.e., along a line or road network). The resulting algorithm was coded in Avenue [TM] and run in ArcView[©] GIS.[77] The algorithm counted the number of neighboring WVCs within a specified scale distance (t) of each WVC and these counts were summed over all WVCs. We standardized the WVC totals by sample size (N) and highway length (RL) to allow for comparison between each highway region. The process was repeated for incrementally larger scale distances up to RL for all five highways. The K-statistic (adapted from Levine and O'Driscoll)[77,185] was defined as:

$$K(distance)_{obs} = \frac{RL}{N^2} \sum_{\substack{i=1 \\ i \neq j}}^{N} \sum_{j=1}^{N} I(d_{ij})$$

where d_{ij} is the distance from WVC i to WVC j and $I(d_{ij})$ is an indicator function that returns 1 if $d_{ij} \leq$ distance and zero otherwise.[185] We used a distance increment of 280 m for all five highway regions to allow for a minimum of 100 d_s bins on the shortest section of highway (i.e. TCH-AB).

To assess the significance of K-values we ran 50 simulations of the above equation based on random distributions of points for each of the five categories. We display results as plots of L versus distance, where L is the difference between the observed K-value and the mean of the K-values for the 50 simulations.[185] Positive values of L indicate crowding and negative values indicate dispersion. We also present the 95% confidence limits calculated as the upper or lower 95th percentile of the random simulations minus the mean of the random simulations.[185] We defined significant crowding as any value of L above the upper confidence limit and significant dispersion as any value of L below the lower confidence limit. The distribution of WVCs was heterogeneous and significantly more clustered or dispersed than would be expected by chance over a wide range of scales (p<0.05, Figure 10). In all highway regions there was significant clustering of WVCs and some significant dispersion. The TCH in Yoho had a small degree of
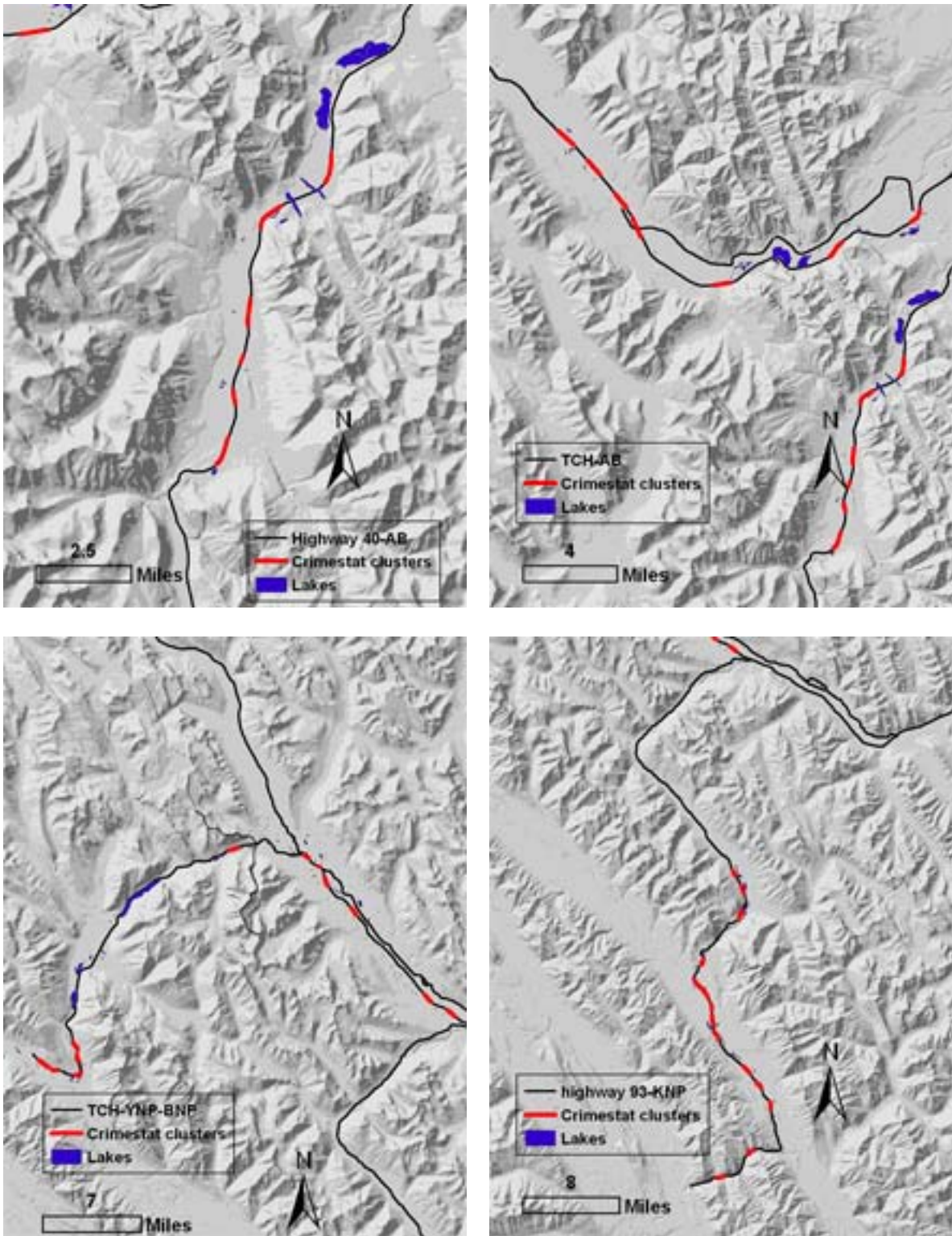
Figure 9: Clusters or hotspots derived from Crimestat III software (Levine, 2004) on each road in each of the five watersheds in Alberta, Canada.

clustering from 1 to 2 km at an intensity of 0.3 km, and significant dispersion at spatial scales from 3–12 km and 18–45 km. This dispersion peaked at an intensity of 7 km. This small scale of clustering can be seen at the westernmost section of the Highway in Figure 8 and Figure 9.

Neighbor K statistics are well suited for the description of 1-dimensional spatial distributions.[200,104,192] The range of scales over which clustering appears significant is dependent on the intensity of the distribution of road-kills.[52,192]

Peaks in L(t); i.e., the intensity of clustering, occurred between km 4 and 5 for TCH in Alberta and the TCH in Banff. This means there was an average of 4–5 extra neighbors within the scale distance of 0 to 10 km on the TCH in Banff and 0-12 km in Alberta. Both these aggregations can be seen in Figure 7 and Figure 8. In Banff they correspond with the section of TCH that bisects a North-South aligned major drainage. At large scale distances, the TCH in Banff National Park (BNP) and Alberta show a random distribution with small scales of dispersions.

On Highway 93 South there is a large peak (27 extra neighbors) in WVC clustering at a scale distance of 0 to 80 km. This corresponds to the bulk of the WVCs that occurred at the southernmost section of Highway 93 in low elevation montane habitat. Further, the highway bisects a key ungulate movement corridor in this area.

The Ripley's K analysis clearly shows the spatial distribution of WVCs along each segment of highway. The large-scale aggregation evident on Highway 93 South in Kootenay shows the importance of broad scale landscape variables such as elevation and valley bottoms in a mountain environment. The scale extent of WVC aggregations in each study area can be used to help determine the scale extent and type of variables to be used in explaining the occurrence of road mortality of wildlife. Further, the locations of high intensity road-kill clustering within each area can help to focus or prioritize the placement of mitigation activities, such as wildlife crossings or other countermeasures, on each highway segment.

Density measures – WVCs per mile segment

For the next two analyses we used the mile-marker data generated from Clevenger et al. (section 3.2 of this report). We divided each of the five highways in the Canadian Rocky Mountain study area into 1.0 mile-marker segments and plotted all spatially accurate WVC data onto each road network. We then moved each carcass location point (WVC) to the nearest mile-marker reference point. We recorded the UTM coordinates of each mile-marker location, and summed the number of WVCs in that mile-marker segment, defined as 800 m (0.5 mile) on either side of the given mile-marker location.
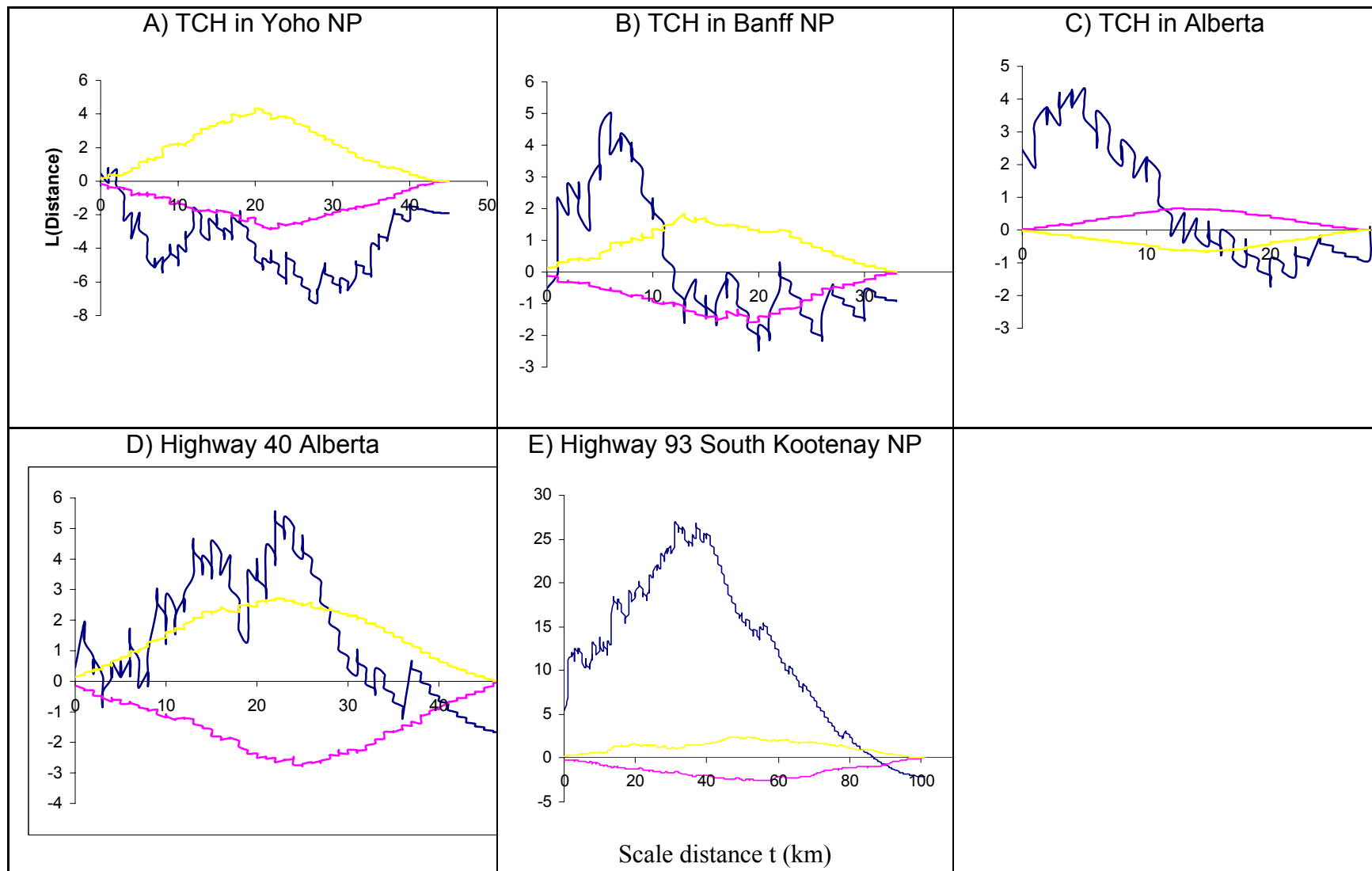
Figure 10: Plotted values of L statistic for the Ripley's K statistic of WVCs from five highways in Canadian Rocky Mountain study area.

For the first analysis, termed the *graduated or weighted mile kill*, we weighted each mile-marker by the summed number of WVCs associated with it and used graduated symbols in Arcview 3.3 to display WVCs along each highway region. A 1:50,000 DEM with a pixel size of 30 m x 30 m was used to derive the hillshade (GIS database management, Banff National Park) for the highways in the study area and used as a backdrop for visualization. Figure 11 effectively shows where the WVCs occurred in relation to the valleys and rugged terrain of the Rocky Mountain landscape. The black arrows in the figures indicate where there was a large clustering of WVCs, which generally was where the highway bisected a valley bottom. The TCH in Alberta has a consistent stretch of WVCs (14-24 road-kills at each mile-marker) from the Banff National Park east boundary to just west of Highway 40. The first westernmost gap in mortality numbers (indicated by the star symbol) is due to the presence of 4.5km of fenced highway with one underpass, while the second gap in WVCs is due to a large lake and river system on the north side of the TCH.

For the second analysis, termed *high kill and low kill* we categorized each mile-marker segment as a 'high kill' or 'low kill' zone by comparing the summed number of WVCs associated with a single mile-marker segment to the average number of WVCs per mile for the same stretch of road, for each of the five highways in the study area. If the summed number of WVCs associated with a single mile-marker segment was higher than the average calculated per mile for the same highway, that mile-marker segment was considered a "high kill zone". Similarly, if the summed number of WVCs within a mile-marker segment was lower than the average for that highway, the mile-marker segment was listed as a "low kill zone". Each low and high kill zone (buffer) was color-coded and displayed on each highway segment along with the associated lakes layer. Other features in the landscape, such as human use and rivers were not displayed because they were not available at the correct scale resolution. The lakes layer was digitized from 1:50,000 topographic maps and only displayed with an 800 m buffer around each highway in each region. In order to compare the level of aggregation of high kill zones between highway regions we measured the mean length of each high kill aggregation. A high kill aggregation was defined as a high kill zone (buffer) with at least one neighboring high kill zone.

When standardized for roadway length, the majority of WVCs occurred on the TCH in Alberta (13.5 road-kills/mile), followed by the TCH in Banff (2.6 road-kills/mile), the TCH in Yoho (2.1 road-kills/mile), Highway 40 (2.1 road-kills/mile) and Highway 93 South (1.8 road-kills/mile). These rates of WVC were used to determine high and low kill segments in each highway region. This analysis produced 97.6 km of high kill zones on all highways in the study area (Figure 12). In 52% of the cases, a high kill zone had a neighboring high kill zone. Highway 93 South had the most high kill zones; however the TCH in Banff had the highest mean length of aggregated high kill zones, while the TCH in Yoho had the lowest mean length of high kill zones (Table 28). The standard deviations on TCH-BNP were high, indicating that the size of aggregations fluctuated highly. Figure 12 shows one main aggregation and a few single high zones on the TCH in Banff. In both the mile-marker visualizations (Figure 11 and Figure 12) the DEM backdrops clearly show that high kills zones are associated with valleys moving perpendicular to the direction of the highway. For example, there is a large aggregation (~13 km) of high kill zones on Highway 93 South in Kootenay National Park which
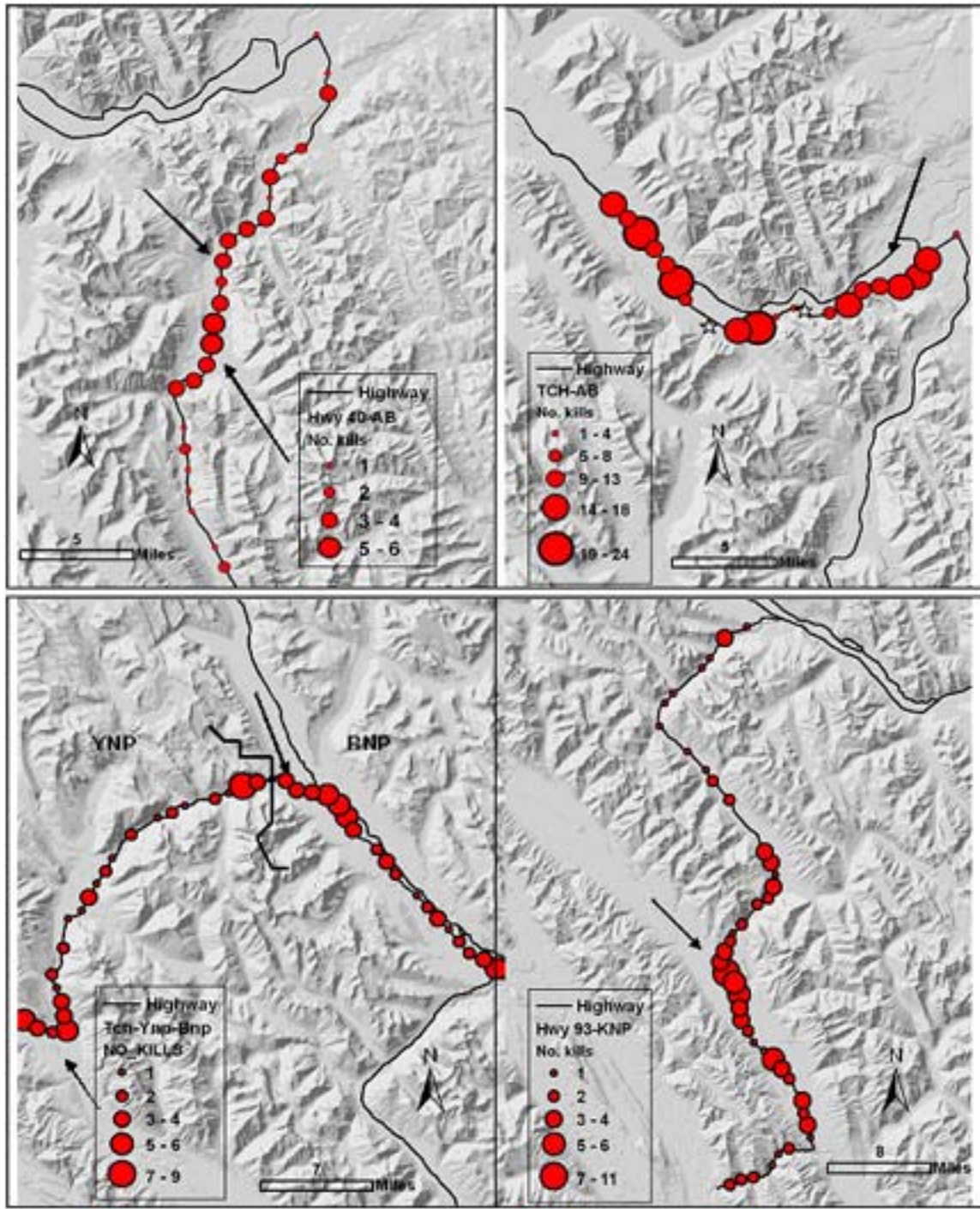
Figure 11: Weighted mile-markers derived from summed collisions by mile marker on each road in each of the five watersheds.

bisects key ungulate ranges in the valley bottoms of the montane region, at an elevation < 1240m.

Comparison of Hotspot Identification Techniques

Visual analysis and observation vs analytical techniques—The pros and cons of the simple visual analysis of WVC vs. more complex or analytical methods were discussed earlier (Simple graphic techniques, one dataset). Essentially with simple plotting of WVCs there is a tendency for road-kill points to overlap and visually mask the importance of segments of highway that have a high density of WVCs. Modeling or analytical techniques permit a more detailed assessment of where WVCs occur, their intensity, and the means to begin prioritizing highway segments for potential mitigation applications. Last, the identification and delineation of WVC clusters, which often vary widely in length depending on distribution and intensity of collisions, facilitates between-year or multi-year analyses of the stability or dynamics of WVC hotspot locations.

Crimestat vs Density-based techniques—Using the nearest neighbor Crimestat® analysis, 42 WVC clusters were produced and together occupied a total of 41 km (15%) of highway in the study area. The nearest neighbor Crimestat® technique was more conservative compared to the mile-marker density analysis; it identified less length of highway as a WVC hotspot. Additionally, the average length of WVC clusters was shorter than the density-based high-kill aggregations; however the Crimestat® analysis produced clusters that were not continuous (Table 28). If we had selected a larger search radius for inclusion of road-kill points, we would have had fewer clusters. Crimestat® also consistently produced fewer clusters of WVCs than the mile-marker density analysis.

Use of either technique for identifying WVC or road-kill hotspots may depend on the management objective. The Crimestat® approach is useful for identifying key hotspot areas on highways with many road-kills because it, in essence, filters through the road-kill data to extract where the most problematic areas lay. The mile-marker density analysis results in identifying more hotspot clusters on larger sections of highway. Although this approach appears to be less useful to management, it may be a preferred option where managers are interested in taking a broader, more comprehensive view of wildlife-vehicle conflicts within a given area. This may be necessary to not only prioritize areas of conflicts but plan a suite of mitigation measures. The location of the larger clusters produced by the density analysis could be tracked each year to determine how stable they are or whether there is a notable amount of shifting between years or over longer time periods. This type of information will be of value to managers in addressing the type of mitigation and intended duration (e.g., short-term vs. long-term applications).

The clusters followed a spatial distribution similar to the mile-marker high kill zones (Figure 9). The degree of overlap between the two techniques was high for 3 of the 5 highways. For example all the clusters on the TCH-Yoho fell within high-kill zone aggregations (Table 28). Similar patterns of overlap were found for the TCH in Alberta and Highway 40 in Kananaskis Country. Less overlap of clusters defined by the two techniques was found for Highway 93 South and the TCH in Banff. These results beg the question: what mechanisms influence the spatial patterns of clusters derived by both
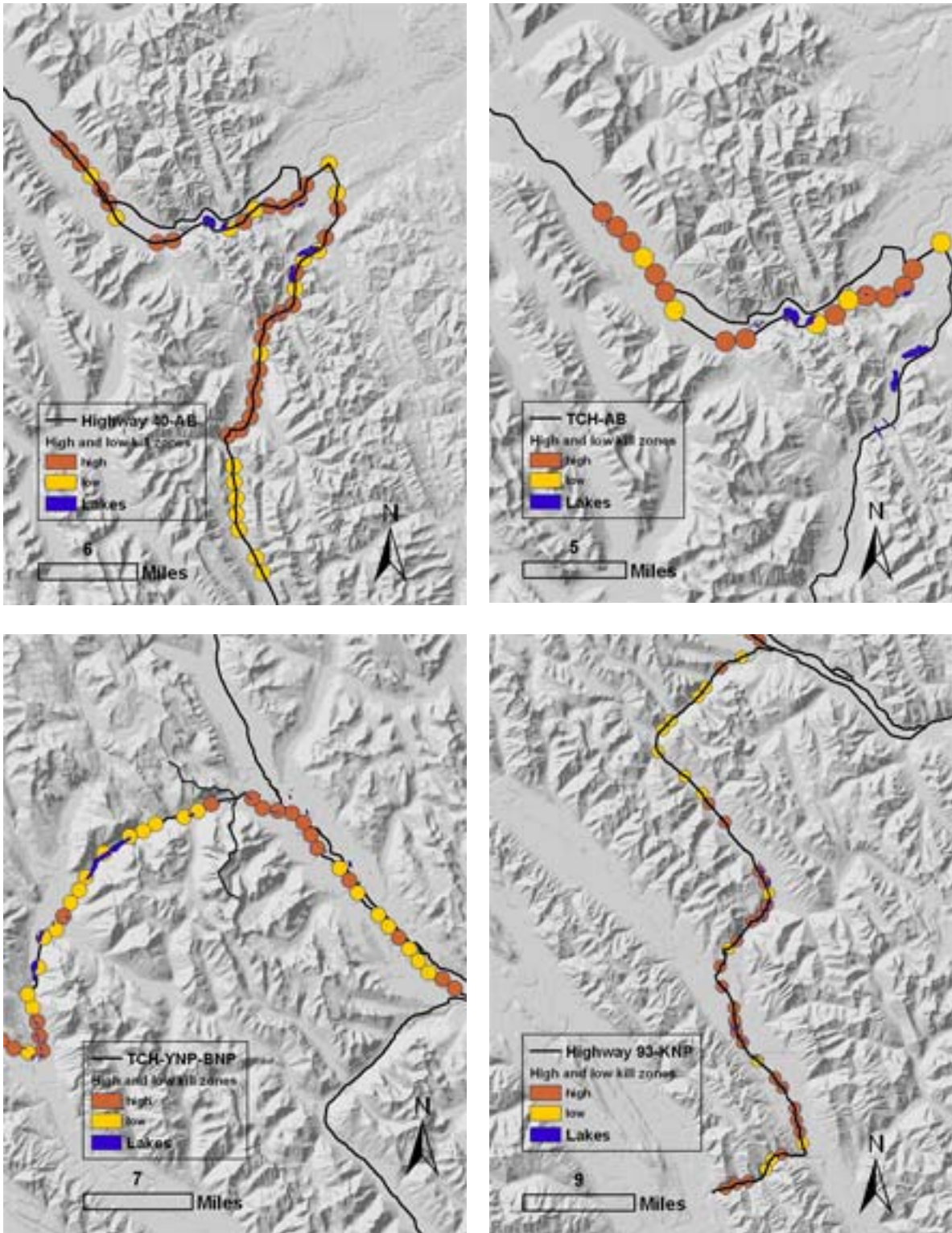
Figure 12: Density of kills at each mile marker on each road in each of the five watersheds.

techniques? Why is cluster overlap high in some areas, but low in others? Both techniques coincided perfectly on the TCH in Yoho (100% overlap), whereas they were most divergent on Highway 93 South in Kootenay National Park (roughly 50% overlap). The overlap of clusters on the other three highways was aligned with either one of the two endpoints above. From inspection of the WVC data on all five highways we suggest that the amount of WVC cluster overlap from the two techniques is likely influenced by the density and distribution pattern of WVCs. High overlap was found on the TCH inYoho, where steep terrain dictates more or less where animals can cross the highway. There are few suitable locations where wildlife can cross the TCH, thus road-kills occur in clearly defined sections. Clusters will naturally overlap or be in proximity since collisions rarely occur outside the key highway crossing areas. On highways that have less topographic constraints and more dispersed wildlife habitat, WVCs will tend to be greater in number and more uniformly distributed than on the Yoho highway. Cluster definition will tend to diverge, and clusters from the two approaches will become spatially isolated. The reason is that the density-based method has a tendency to accommodate outlying or marginal WVCs that normally would not cluster using Crimestat®.

Table 28: Descriptive statistics of ungulate-vehicle collision clusters generated by Crimestat®

Highway	Crimestat clusters (N)	Mean length of Crimestat clusters ± SD (km)	Density Analysis Clusters (N)	Mean length of density Analysis clusters ± SD (km)	Cluster overlap index [b]
TCH [a] Yoho	6	1.00 ± 0.32	7	2.80 ± 1.33	1.00
TCH Banff	6	0.92 ± 0.38	11	4.40 ± 3.98	0.64
TCH Alberta	7	1.32 ± 0.14	12	3.84 ± 1.63	0.90
Highway 40	6	0.96 ± 0.42	13	4.16 ± 3.29	0.85
Highway 93 South	17	0.86 ± 0.39	19	3.49 ± 2.34	0.56

[a] TCH=Trans-Canada Highway.
[b] Cluster overlap index (cluster length$_{density\ analysis}$ /cluster length$_{Crimestat}$). 1.0 = 100% overlap, 0.00 = no overlap.

Hotspot Identification and Patterns for Different Species and Landscapes

For this analysis, we selected one clustering technique (Crimestat®) and conducted a hotspot analysis for two different datasets: WVC data from Canadian Rocky Mountains and Caltrans DVC data for Northern California. The data are described above in the Study Area Section and shown in Figure 13. We used Crimestat® version III [146] to determine the location of DVC hotspots along SH 89 in Sierra County, California and the five highways in the Canadian Rocky Mountains. For visual comparisons we plotted of all DVC data along SH 89 in Sierra County, California. Below we describe the hotspot patterns and configurations, and examine how they may differ by species and the two landscape types.

The mean number of DVCs was 25.7 kills/mile for the 26-year period and equates to roughly 1 kill recorded per mile per year. There was a high degree of overlap of DVC points on SH 89 based on the simple plotting of collisions. Similar to the simple plots made of WVCs in the Canadian Rocky Mountains, it was difficult to identify where the hotspot actually occurred. The excessive overlap and what appears to be continuous clustering of DVC points was most likely a result of the high number and density of
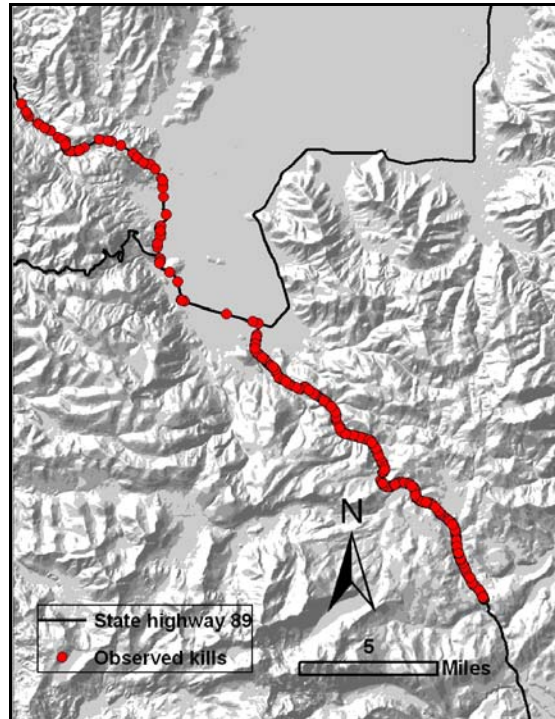
Figure 13: Spatially accurate locations of deer vehicle collisions on State Highway 89 in Sierra County, California.

DVCs for the relatively short stretch of highway. Note that the California DVC data were obtained from a 26-year period, compared to 500+ points from the Canadian study area, obtained from > 250km of highway during a 7-year period.

Nine Crimestat® clusters with a mean length of 1.34 ± 0.26 km (Table 29) were created on California U.S. Highway 89 and occupied more than half of the 18 km section. Hotspots were associated with a variety of terrain types, but largely with mountainous terrain. Some of the hotspot clusters appear to be associated with valley bottom habitats, but a substantial amount can be linked with river courses in rugged terrain. Given the large number of hotspots identified along SH 89, management would need to prioritize which ones represented real safety and wildlife conservation concerns. The large 26-year dataset clouds the picture by having numerous DVCs on one stretch of highway. A sequential analysis of DVC hotspots in 5-year increments would help identify trends and patterns in hotspot distribution and bring to light the more problematic sections of highway.

Table 29: Descriptive statistics of the Crimestat® clusters delineating deer-vehicle collision hotspot clusters on State Highway 89, Sierra County, California

Highway	Number of clusters	Mean cluster length ± sd (km)
Highway 89	9	1.34 ± 0.26

Interpretation, Appraisal, and Applications

GIS Linkages to Hotspot Data

The collection of wildlife-vehicle colllision carcass data is important for many reasons, but serves as baseline information to guide the planning and future management of roadways. Wildlife-vehicle colllision data can be used to quickly identify coarse scale problematic areas on roads, much like we have demonstrated with several of the techniques shown above. This may help efficiently guide planning and decision-making if transportation improvement plans encompass designated WVC hotspots. In this report, we explored ways GIS-based information can be linked to hotspot data and their applications. With the hotspot data collected, stored in a database format, the next logical step is look at the types of GIS data that can be used to perform analyses for transportation management. These include coarse scale or preliminary analyses that can be used in rapid assessments to identify wildlife-transportation conflicts or streamlining of wildlife and safety needs in transportation planning. They can be considered a preliminary analysis because often times they are not comprehensive or statistically rigorous approaches, but rather are useful initial examinations of the relationships between wildlife-vehicle colllisions and the natural and man-made environment around them. The type of data needed to identify the location of hotspots for wildlife-vehicle colllisions need not be spatially accurate, because mitigation measures usually address problematic areas that cover several miles of highway. For this reason, data accurate to the 1.0 mile-marker is sufficient. Existing agency road-kill data can be useful for coarse-scale mapping to identify problematic areas and benefit from planned infrastructure improvement capital.

Bridge rebuilding and retrofits are excellent examples where hotspot information can be utilized to identify areas where highway improvement projects can improve motorist safety and habitat connectivity for wildlife. The periodic reconstruction of highway bridges that span over waterways are excellent opportunities to benefit from structural work projects to improve wildlife and fish passage along riparian corridors by widening bridge spans or habitat enhancement.[98]

Today, state transportation planning exercises such as STIP (Statewide Transportation Improvement Program) are identifying key areas for transportation infrastructure investments. At the same time, state natural resource agencies are mandated by Congress to develop comprehensive wildlife conservation plans that address a full array of wildlife and habitat conservation issues.[6] Coordination of both network plans in a timely and integrated fashion would be a significant contribution to streamlining environmental concerns in transportation planning. A recent example of integrating agency road-kill information with standard GIS data for sustainable transportation planning took place in Vermont.[9] The transportation department (VTrans) developed a centralized database of wildlife road-kills, wildlife road crossing, and related habitat data for individual species throughout the state. In order to expand and improve

wildlife road-kill reporting data, a partnership and recording procedures were developed with VTrans field and district staff enabling them to record a new array of wildlife road-kill information. With their wildlife road-kill information they performed a GIS-based "Wildlife Linkage Habitat Analysis" using landscape scale data to identify or predict the location of potentially significant Wildlife Linkage Habitats (WLH) associated with state roads throughout Vermont.

The project relied on readily available GIS data including: (a) land use and land cover data, (b) data on developed or built areas, and (c) contiguous or "core" habitat data obtained from the University of Vermont. The components that comprised the overall GIS data layers were then ranked in accordance with their relative significance to creating potential WLH. The analysis, in conjunction with the newly updated wildlife road-kill data, provided a science-based planning tool that will aid VTrans in understanding, addressing and mitigating the effects of roads on wildlife movement, mortality, habitat and public safety early in the design process for transportation projects.

There are a variety of GIS modeling approaches today, from simple such as the one taken in Vermont to more complex models requiring high-resolution and spatially-explicit data. Most GIS modeling used for transportation planning purposes tends to be coarse scale and do not require specially developed GIS data layers.[13,65,212] Like GIS-based data on animal movements, hotspot information can be used to identify problematic areas and thus integrate mitigation where highway improvement capital will be invested. Hotspot areas that are associated with existing below-grade structures (e.g., drainage culverts and bridges) can be identified by linking GIS data, allowing structural and land planning recommendations to be made to improve permeability at unsuitable passage structures.

In another example, wildlife-vehicle colllision data were used along Interstate 90 in Washington State to evaluate the relationship between hotspot clusters and important landscape characteristics.[214] They mapped road-kill density using the approach we described earlier, classifying segments as high, moderate, or low ungulate-kill density. A "classification tree analysis" (using S-Plus 2000) was used to determine the importance of 10 landscape-scale variables (GIS layers comprising road and landscape features) in the study area. Classification tree analysis is well suited for analysis of GIS spatial data. Being a nonparametric technique, it involves no assumptions of normal distribution, works well with categorical data, and is robust to the relatively subjectively determined sample sizes inherent with GIS raster data. Further, linking these coarse scale hotspots with environmental data (e.g., terrain, habitat suitability, zones of animal movement) can provide a relatively quick and reliable project-level or district-level assessment of how to prioritize mitigation activities directed at wildlife-vehicle colllisions.

Conclusions

In this section we draw on the key points of our research to suggest guidelines for hotspot application. Data on hotspots of WVCs can aid transportation managers to increase motorist safety or habitat connectivity for wildlife by providing safe passage across busy roadways. Knowledge of the geographic location and severity of WVCs is a prerequisite for devising mitigation schemes that can be incorporated into future infrastructure projects (bridge reconstruction, highway expansion). Hotspots in close

proximity to existing below-grade wildlife passages can help 1inform construction of structural retrofits that can help keep wildlife off roadways and increase habitat connectivity.

The WVC data that transportation departments currently possess are suitable for meeting the primary objective of identifying hotspot locations at a range of geographic scales, from project-level (<50 km of highway) to larger district-level or state-wide assessments on larger highway network systems. The spatial accuracy of WVCs is not of critical importance for the relatively coarse-scale analysis of where hotspots are located. To determine site-specific factors that contribute to WVCs, then more spatially accurate data will be required. Thus, WVCs referenced to a mile-marker system will be of sufficient quality for transportation agencies to begin identifying where problematic areas for motorists and wildlife are on the highways they manage. WVC data with greater spatial accuracy are equally useful in determining the location of hotspots; however they are not essential to begin examining highway-wildlife conflict areas.

We have outlined and described various techniques available that can help delineate WVC hotspots. Simple plotting of collision points is a relatively straightforward means of identifying problematic areas, however, as sample sizes increase the tendency for road-kills to overlap (hide other points) increases. The length of highway examined, intensity of road-kills, and time period of data collection all influence the density of collision points. Other factors such as terrain, wildlife abundance and wildlife habitat quality adjacent to the highway will further affect the spatial distribution (random/continuous or non-random/clustered) of WVCs on a given highway. Modeling or analytical techniques permit a more rigorous assessment of where WVCs are likely to occur, their intensity, and the means to begin prioritizing highway sections for mitigative actions. The nearest-neighbor Crimestat® method essentially pinpoints the location of WVC hotspots, whereby the segmental analysis of WVC densities provides a more comprehensive evaluation of mitigation options and prioritization of mitigation schemes based on cost-benefit, scheduling of transportation projects, or severity of motorist safety concerns.

Transportation departments should continue collecting WVC data (both reported vehicle crashes and carcass collection data), but need to be more systematic about collection procedures. In many state agencies, WVC data collection is not consistent throughout the state and varies in intensity and data quality from district to district. Systematic data collection and protocols will allow for greater management benefits and utility of information for transportation planning and incorporating mitigation strategies in transportation projects with motorist safety and wildlife protection concerns.

We are not aware of state transportation departments that have consistently used WVC hotspot data for decision-making in transportation projects or strategic planning with future infrastructure plans such as STIP in mind. The collection of WVC data systematically and comprehensively will provide important baseline information for planning and streamlining environmental mitigation in projects, and furnish critical data (pre-mitigation reference) for ultimately assessing the performance of mitigation measures that are adopted.

INFLUENCE OF ROADS ON SMALL MAMMALS (3.4)

Lead:
Utah - J. A. Bissonette, Silvia Rosa, Carrie O'Brien
British Columbia - Nancy Newhouse, Trevor Kinley

Abstract

Highways have the potential to affect the demographics and distribution of small mammals. We wished to investigate what influence highways have on the relative abundance and diversity of small mammals and how far any observed effect might extend into adjacent habitat. In Utah, we established study sites in sagebrush-steppe vegetation at varying distances from the road as well as along a 2.4m right-of-way (ROW) exclusion fence along interstate highway I-15. We did not sample the verge on the highway side of the ROW for safety reasons because of high traffic volume. The sampling transects were located in very dry xeric sites.

In British Columbia, we established trapping transects at eight sites within the ROW, at 25m from a 2-lane highway centerline, and in the forest at 50, 300 and 600m from the centerline. Identical transects were established at 8 sites in and near a high-voltage transmission-line ROW lacking a developed road. Transects were located in predominantly mesic sites in mid-seral coniferous forest. Both the highway and transmission line ROWs were approximately 60m wide.

In Utah, we captured 484 individuals of 13 species. Our results show different trends of species diversity from one year to the next. During 2004, the diversity of species was highest further from the road in direct contrast to 2005, when diversity was highest closest to the road. Density and abundance data also differed between years and species. When we compared density in three vegetatively distinct areas, sites with higher habitat quality had significantly higher small mammal densities. Overall, it appears that roads per se have little effect on small mammal density. Rather, microhabitat conditions (i.e., higher habitat quality) appear to be most responsible for density responses. The results are similar for British Columbia (B.C.) where we captured 401 individuals of 11 species, typically in a clumped distribution. Our results show that the effect of the highway ROW or transmission-line ROW appeared to be negative for most species and potentially neutral to positive for others, with total species diversity lower in the ROWs than forest. However, there were no consistent patterns to indicate further change within the forest as distance from the ROW increased. If there were any demographic effects caused by this relatively low-volume, 2-lane highway other than those due to the simple shift in habitat type from forest to graminoid (grass) cover, they were less evident than were the effects of site or microhabitat conditions. Microhabitat, or other local conditions that vary among sites and transects and that remain independent of ROW, appeared to be stronger than, or at least mask, any effects related to the ROW. For the most common and most habitat-generalized species, the deer mouse (*Peromyscus maniculatus*), there were no strong indications of an effect of distance from the highway or transmission line, nor evidence of any effect attributable to the highway that was not evident at the transmission-line sites. Impacts due to the highway itself may exist for some species, but large samples and highly consistent habitat conditions would be required to detect them.

Introduction

Highways have the potential to affect the abundance and distribution of small mammals. Differences in the density of many small mammals have been reported when road verges have been compared to the habitats beyond them.[2,1,19] This may be due to structural or vegetative differences in habitat, water runoff, or the additional impact of noise, vibration, deposition of road salt or other chemicals, or differential rates of predation between the verge and adjacent land. Highways may also act as barriers or partial barriers to movement.[186,143,153,103,49,107,170,36] This may indirectly lead to population impacts due to the reduced probability of genetic flow and demographic 'rescue' (inflow of animals to counter local extirpations caused by random events) for small populations. Direct mortality of small mammals on the highway surface[186] appears to have variable effects on population density[2], as well as demographic changes such as the disproportionate loss of sex or age classes that tend to disperse. While it is well established that highways contribute to such impacts,[186,143,153,103,49,107,170,36] to what extent is not entirely clear. Questions remain as to what impact highways have on species diversity found in the dry forested ecosystems typical of much of the mountainous region of western North America, to what extent the effects extend beyond the highway, and if the impacts are due to the highway specifically or to the presence of a disturbed ROW generally.

Both direct effects (animal mortality) and indirect effects influence animal response to the roaded landscape. *Direct effects* such as actual road kills, impact all species, but collisions with larger wildlife species (deer, elk, moose, caribou, and large carnivores) pose the most risk to driver safety and result in higher auto damage and human injury. Knapp (http://www.deercrash.com/states/data.htm) showed that for the five-state Upper Midwest, 121,584 deer-vehicle crashes caused over $206.6 million in vehicle damages, but more importantly, resulted in 35 human deaths and 4,666 injuries in 2003-2004. Direct effects are on the rise, and the costs to citizens will only increase unless effective mitigation is put into practice across the continent. Our analyses of Tasks 1, 2, and 3 of the project provides a synthetic assessment of direct effects, viz., road kill, that we will incorporate into the guidelines. Indirect effects of roads on wildlife putatively are as important to ecological communities as are direct effects such as mortality. The most commonly reported *indirect effects* include: 1) loss of habitat, 2) reduction of habitat quality, 3) fragmentation of once 'more continuous' habitat with associated increases in edge density and edge buffer effects, 4) habitat disconnectedness, and 5) barrier effects. One complication is that the landscape consequences from indirect effects are interrelated suggesting that parsing out the contribution of each effect will take a long-term experimental approach. This is not possible or feasible in the time available for this project. However, permeability can be assessed and species responses to roaded landscapes can be measured. The null hypothesis that we will test is that indirect effects, taken as a whole, have little significant effect on animal population response. We define significant as greater than 10% deviation, after background variation has been taken into account. Here are the first level predicted responses classed by indirect effect:

1) If *habitat quality* is reduced, we expect species presence or absence, composition, and relative abundance, will change at increasing distances from the road

2) If _habitat fragmentation_ is increased, we expect that measures of heterogeneity, as measured directly from digitized aerial photos or recent satellite images, will change significantly

3) If there are _increases in edge_, it is possible to document the differences. Species presence, abundance, and composition should change. GIS analyses could also be used

4) If there are _edge buffer effects_, we expect that there will be a zone close to the road where species presence, abundance, and composition will be dramatically influenced

5) If the roaded landscape results in increased _habitat disconnectedness_, it can be measured. We predict that differences within the landscape matrix will be correlated with different occupancy rates by species

6) If there are _barrier effects_, we predict that species presence or absence, composition, and relative abundance will be significantly different when both sides of the road are compared

As is evident from our predictions, assessment of causality to a <u>specific</u> indirect effect is not possible or practical at this time within the time schedule and funding available. The summation of the effects, however, is easy to document. We can compare animal response near roads with a control response to a non-roaded area. By response, we mean the number of small mammal species and their relative abundance. Jaeger et al.[133] explained that roads and traffic can affect the persistence of animal populations in four distinct ways: a) a decrease in habitat amount and quality, b) increased mortality, c) barrier effects that prevent animals from accessing resources across the road, resulting in d) fragmented and subdivided populations.

The work in Utah and British Columbia makes it possible to determine the impact of roads on habitat quality for small mammals at varying distances from the road. If habitat quality has declined, we should expect a decline in the numbers and relative abundance of small mammal species nearer to roads. To investigate these questions, we compared the relative abundance of small mammals at varying distances from a major interstate highway in Utah, and a 2-lane highway and high-voltage transmission-line ROW in British Columbia. This allowed us to compare the effects of two very different types of roads while simultaneously addressing the effect of distance from the ROWs.

For this field effort, we selected sites in two areas, (Western British Columbia and the Intermountain Region of Utah) to determine if any general response of small, terrestrial vertebrates exists for arid and mesic sites. There is tremendous variation across the North American continent in terms of vegetation cover, topography, levels of urban development, land use practices, road density, traffic volume, as well as differences in the typical species diversity, richness, and abundance in local areas. Yet, it is impossible with current budget restraints to capture that entire variation. Nevertheless, this is the case with most ecological studies and we contend that there is an imperative to capture the basic ecological responses and apply those fundamental principles to mitigation and management. In other words, as we suggest in the proposal on page 8: "Providing guidance on the use and effectiveness of wildlife crossings to mitigate habitat fragmentation and reduce the number of animal–vehicle collisions involves thinking in a

context sensitive framework that is based on sound ecological principles." Our approach is to develop ecological principles that have conceptual generality and that can be applied broadly. <u>The caveat, of course, is that guidelines that we develop will need to include guidance on the necessity of gathering local, empirical data that will inform the programming, planning, design, and construction phases of building, upgrading, and the maintenance of roads.</u>

For this effort, sites characterized by natural vegetation located next to roads were selected and compared to sites distant from the road. Indirect effects have been suggested to operate within 100m of a road yet, we have designed our sampling protocol to detect changes that may occur up to 600m or more from the road. Small mammals have relatively small home ranges and limited mobility and we expect that results should be evident within 600m from the road. We measured:

1) small mammal species presence or absence

2) small mammal species composition

3) small mammal species relative abundance

In both Utah and British Columbia, we sampled at increasing distances from the road to address indirect effects 1 and 4:

1) If <u>habitat quality</u> is reduced, we expect species presence or absence, composition, and relative abundance will change at increasing distances from the road

4) If there are <u>edge buffer effects</u>, we expect that there will be a zone close to the road where species presence, abundance, and composition will be dramatically influenced

Research Approach: Methods and Data

Permeability and Small Mammal Trapping

The work for this segment was conducted in Utah and British Columbia in two very different habitats. Utah is located in the Intermountain West of the US. The study site is mostly comprised of sagebrush (Artemesia spp.) habitat and the road verge (ROW) is largely non-vegetated. The British Columbian site in Canada, conversely, is heavily forested with a heavily vegetated road verge. We adapted our sampling scheme to maximize capture of small mammals for these very different sites. Below we describe how we conducted the field work in each site. We began work in Utah in 2004 as part of an ongoing study and continued in 2005. In British Columbia, we conducted the field work during summer 2005.

<u>Utah</u>

This study was conducted in the high elevation desert region of the Great Basin of western Utah near Beaver, Utah (38°16'N latitude and 112°37'W longitude) adjacent to Interstate 15 (I-15), a 4-lane divided highway with an average of 16,015 vehicles/day. Elevation ranged from 5,500 to 6,300 ft (1,700 to 1,900m). Vegetation cover was

dominated by big sagebrush (*Artemisia tridentata*) with an occasional inclusion of pinyon pine *Pinus edulis* and juniper *Juniperus osteosperma* trees. The road verge included sagebrush and grass-like vegetation or was completely non-vegetated. The weather was characterized by below freezing temperatures and snow cover during the winter and high temperatures during the summer. Maximum temperatures rarely exceeded 100°F (38°C) and minimum temperatures were usually above -10°F (-23°C), with annual mean temperature of 47.4°F (8.6°C). Annual precipitation (in the form of rain and snow) was less than 12 in (305 mm), and came primarily during winter, early spring, and late summer. Relative humidity was very low and evaporation potential was high. Prolonged periods of drought are frequent in the region. The soil on the trapping sites was composed mainly of fine sand deposits with occasional volcanic rocky areas. Study sites were established in sagebrush-steppe vegetation along interstate highway I-15, centered on UTM (NAD27) X=354471 Y=4248267. Small mammal sampling was conducted exclusively in sagebrush habitat on both sides of the road (Figure 14).
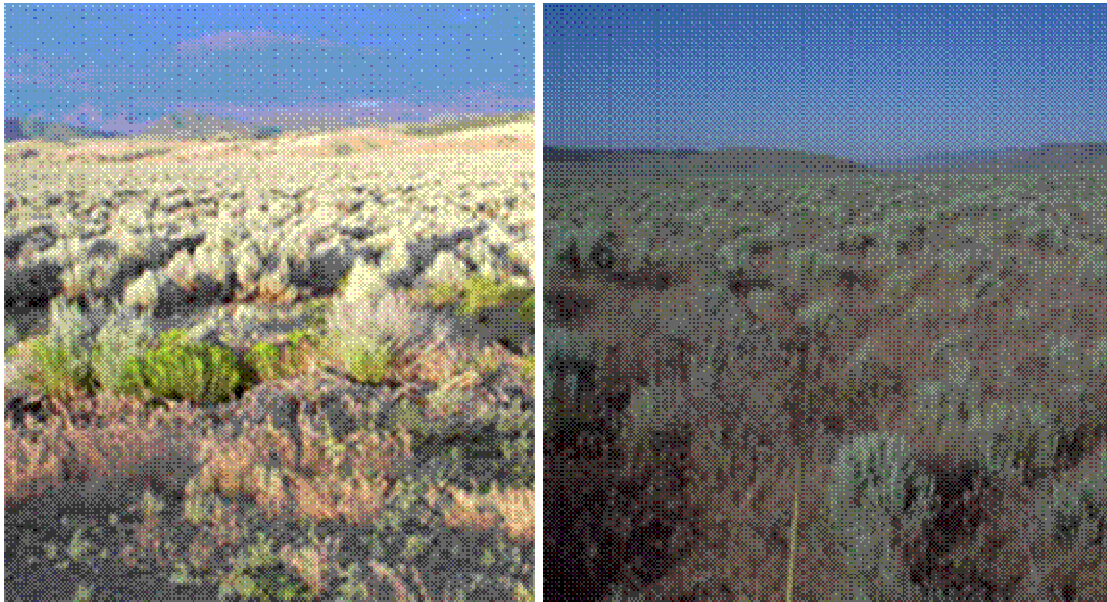
Figure 14: Sagebrush habitat in southwestern Utah where small mammal trapping was conducted

We trapped from 30 May to 14 August in 2004 and from 17 June to 18 August in 2005. The trapping design was altered between the 2004 and 2005 field seasons to maximize the useful information gleaned. In 2004, trapping webs were used to assess road influence on small mammal communities. In 2005, we used trapping lines to compare our results with the British Columbia trapping scheme. During summer 2004, 12 transects were completed with two trapping webs per transect, for a total of 24 webs. The first trapping web was placed at 50m (Close) and the second at 400m (Distant) from the road (Figure 15). Each web was composed of eight segments extending 50m outwards from a central point. Each segment had five trapping stations, each located 5, 10, 20, 30, 40, and 50m from center, with one trapping station located at the center of the web for a total of 98 traps [(1/2 lethal (snap) and ½ non-lethal (live)] traps per web and a total of 2,352 traps for the 24 webs. During summer 2005, three trapping lines were placed parallel to the road along each of 5 transects (Figure 15) for a total of 15 trapping lines.

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Lines were placed at increasing distances from the exclusion fence; at zero meters (Close), 200m (Mid), and at 600m (Distant). Each line was 150m in length and contained 30 traps total, for a total of 450 traps for the 15 trapping lines. We completed a total of 8,406 trap-nights: 7,056 in 2004 and 1,350 in 2005. For safety reasons, the ROW verge between the road edge and the 2.4m deer exclusion fence was not sampled because of very high traffic volume.

All traps in both sampling schemes were baited with a mixture of horse grain and peanut butter, and checked on three consecutive mornings and afternoons (lethal traps only). Upon capture, all animals were identified, sex determined, measured, marked, and released. Dead animals were removed from the study site.
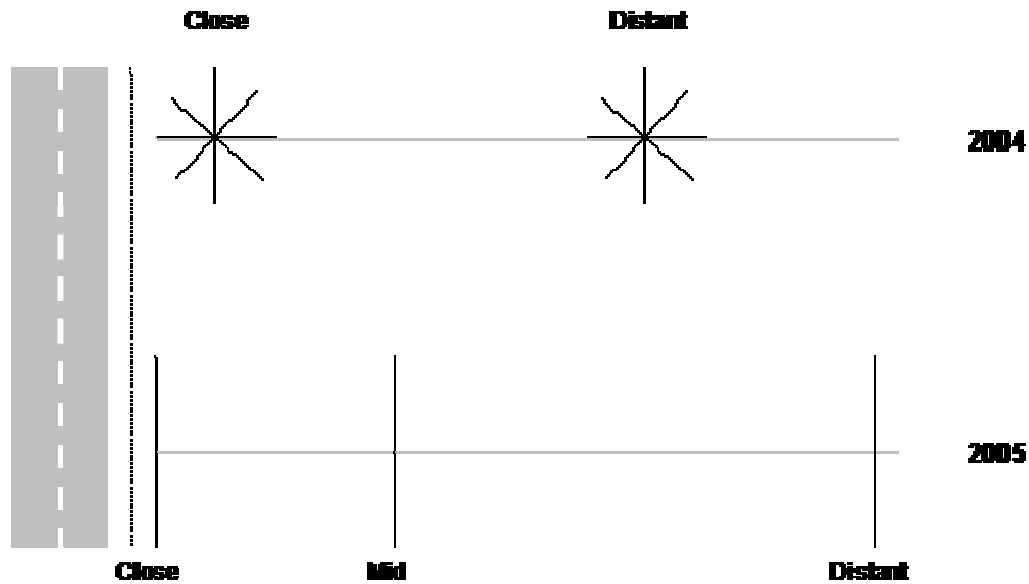
Figure 15: Schematic representation of sampling schemes in 2004 and 2005

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Data Analysis—Web-based data analysis for 2004 employed a distance method described by Anderson *et al.* [5] which utilizes first capture locations for each individual and distance to center. Program DISTANCE 4.1 [40,41] was used to calculate densities and variance estimates. For analysis, capture data was pooled in 'Close Webs' and 'Distant Webs' due to low number of animals sampled in each web. Estimation was only possible for the most abundant species (i.e., > 30 captured individuals per pooled database) or for all small mammals combined. Density estimations in program DISTANCE were obtained by every possible combination of models (uniform, half-normal, hazard, and negative exponential), and adjustment terms (cosine, simple polynomial, Hermite polynomial - See Appendix F). Final model selection was based on Akaike's Information Criterion (AIC) value and on model performance. Each data set was used in its entirety without truncation. Intervals used in DISTANCE (0.0, 7.5, 15, 25, 35, 45m) were the midpoints between trap-stations. Resulting densities in Close and Distant Webs were tested for significant differences using Wald test.

Analysis for trap line data in 2005 was conducted using a closed population mark-recapture method in Program MARK 4.3.[243] Closure was assumed given that trapping occurred in a sufficiently brief interval, and the removals were known and accounted for in the analysis.[246] A Huggins Closed Capture estimator was applied to obtain abundance estimates and the respective confidence intervals. Capture data was pooled in three groups representing increasing distances from the road (Close, Mid and Distant). Estimates were obtained for the null and other models to represent variability in capture and recapture probabilities. Models that did not converge were discarded. Remaining models were selected based on AIC value and averaged to obtain final estimates of abundance. Differences in abundance estimates were tested using Wald test.

The Shannon-Wiener diversity index (H) was used to compare community diversity at different distances from the road.[17] The index was calculated for each web or trap-line in all transects, and tested for distance-related differences by the Wilcoxon paired-sample test for 2004 data, and Friedman's test for 2005 data.[250] The least significance difference (LSD) multiple comparison test was used with 2005 data to determine if any pair of distances (close vs. mid; close vs. distant; mid vs. distant) was significantly different.[218]

British Columbia

Field sites in British Columbia were located in the Rocky Mountain Trench of southeastern B. C. at elevations of 830 to 1000m, centered on 50.1° N by 115.8° W. Eight study sites were selected for each of two treatments (Figure 16): along a 30km stretch of Highway 93/95 (mean total ROW width 57m ± 9m SD, including 12m wide highway), and along 40km of a high-voltage transmission line (mean ROW width 62m ± 8m SD). The transmission-line ROW was comprised of a rough track, but no developed road (Figure 16, right panel).
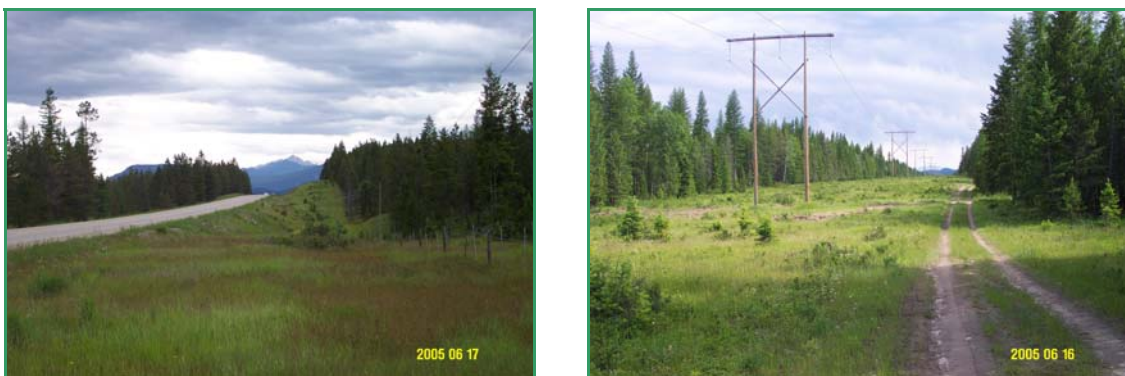
Figure 16: Right-of-way types: Highway 93/95 (left) and high-voltage transmission line (right).

We consistently set the 50m transect 20m into the forest to standardize its distance from a change in habitat type. This resulted in a 49m average from the highway centerline, or 51m from the transmission line centerline. Sites were not randomly selected. Rather, we used 1:20,000 orthophotos and field inspections to locate all points along the transmission line. The study area is predominantly mesic soils, had continuous

or nearly continuous forest cover, and there are no minimal or major roads, large cut-blocks, significant habitat shifts, or other sampling sites within 600m radius on at least 1 side of the ROW. We selected an equal number of highway sites fitting the same criteria.

Each transect was 150m long and oriented parallel to the ROW (326-360°). We established 16 trap stations per transect (10m intervals), with two snap traps (Snap-E Mousetrap, Kness Mfg. Co., Inc., Albia, Iowa) occupying each trap station. We used a grease gun to bait traps with a mix of peanut butter and rolled oats, placed them unopened for 1 week, replaced the bait, and left them unopened for an additional week (i.e. a 2-week pre-bait). We then baited the traps again and set them for 2 nights, checking them each morning. Animals trapped were removed, tentatively identified to species and bagged, then positively identified, sexed, weighed and measured later on the day of capture. We completed all capture work on 14-18 June, and 4-8 July 2005.
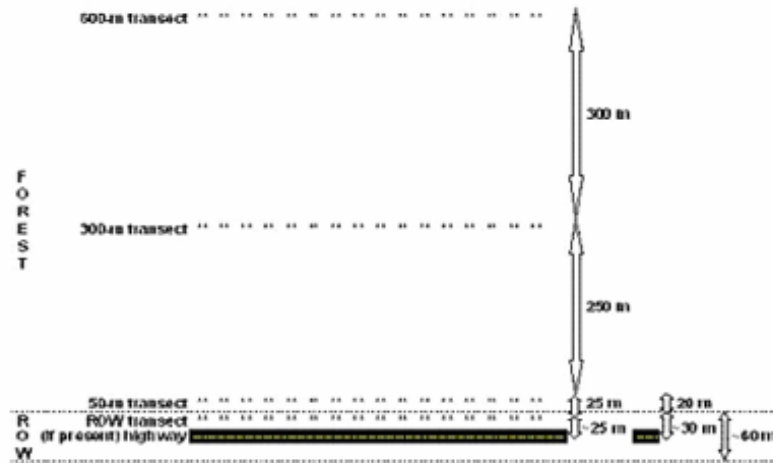
Figure 17: Schematic of site layout for a highway site (not to scale).

The study site lies within the Interior Douglas-Fir biogeoclimatic zone (IDF) in the province's dry climatic region.[35] Within the IDF, six 'site series' (descriptors of potential climax vegetation and soil moisture) have been described. We judged the forested portion of all sites to historically be comprised of the same predominant site series; Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine, (*Pinus contorta*), pinegrass (*Calamogrostis rubescens*), and twinflower (*Linnaea borealis*). However, due to topographic variability, past wildfires, and partial-cut logging, study sites were mid-seral mixes of Douglas-fir, lodgepole pine, western larch (*Larix occidentalis*), and ponderosa pine (*P. ponderosa*), with a minor component of trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*). We did not measure habitat variables, but did record general habitat conditions subjectively. Crown closure was typically 40 to 60%, with portions of some sites ranging from about 10 to 80%. At all sites the dominant understory plant was pinegrass with roughly 5 to 20% cover, but up to approximately 50% cover in some small openings of past disturbance. Other common understory species in all sites included soopolallie (*Shepherdia canadensis*), birch-leaved spirea *(Spiraea betulifolia)*,

common snowberry (*Symphoricarpos albus*), saskatoon (*Amelanchier alnifolia*), Douglas-fir saplings and heart-leaved arnica (*Arnica cordifolia*). Tall Oregon grape (*Mahonia aquifolium*), showy aster (*Aster conspicuus*), twinflower, wild strawberry (*Fragaria virginiana*), and a variety of mosses contributed to the greater ground cover in moister microhabitats or cool aspects. Bluebunch wheatgrass (*Agropyron spicatum*), junegrass (*Koeleria macrantha*), arrow-leaved balsamroot (*Balsamorhiza sagittata*), and kinnikinnick (*Arctostaphylos uva-ursi*) were more commonly present in drier locations with a sparse understory and less pinegrass. Small patches under dense Douglas-fir cover, had essentially no understory. While downed woody debris was sporadically present, there was typically little of this due to the relatively young forest age and its history of past disturbance. All ROWs were predominantly vegetated by wild and/or agronomic grasses and wild strawberry, with variable cover of other forbs, no trees or downed woody debris, and minimal shrub cover.

Highway and transmission-line sampling was equally distributed within the trapping period. The most recent data for highway traffic volume was recorded in 2001, approximately 25km south of the southernmost highway site. Traffic volume averaged 1791vehicles/day annually, including a peak of 2043 vehicles/day during July and August (S. Daniels, Ministry of Transportation, Cranbrook, British Columbia, unpublished data). Traffic volume along the transmission line was essentially nil (estimated 1-5/day average on an annual basis; we saw < 1 vehicle/site/day of trapping or baiting). We compared the number of species trapped (and abundance of each) among transects and among treatments. Where sample sizes permitted, we also compared weights of adult males, weights of adult females, sex ratios and juvenile:adult ratios among transects and treatments using t-tests and chi-squared tests as appropriate using the program JMP IN (SAS Institute, Inc., Cary, North Carolina). Research was conducted under permit CB05-9954 issued by the British Columbia Ministry of Water, Land and Air Protection.

Findings and Results

Utah

In 2004, a total of 11 species were captured; two species exclusively in areas close to the road (rock squirrel and sagebrush vole), and two species exclusively distant from the road (piñon mouse and white-tailed antelope squirrel). The remaining seven species were captured at both distance classes from the road (Table 30). During 2005, (Table 31) a total of seven species was captured with three species caught only close to the road (desert cottontail, jackrabbit and desert woodrat).

Results from density and abundance comparisons between different distances from the road indicate that, in most cases, small sample sizes prevented a precise estimation to discern clear trends. Despite the lack of statistical significance, in 2004 *Peromyscus maniculatus* had lower densities closer to the road (Figure 18) while *Peroghnatus parvus* exhibited the opposite trend (Figure 19). Results of Shannon-Wiener diversity index (H) analysis revealed there were variations in diversity trends in different years. During 2004, the Shannon-Wiener diversity index (Table 32) was significantly higher in areas distant from the road (Wilcoxon Z= -2.224, p=0.026) as compared to results in 2005 (Table 33) in which diversity peaked close to the road (Friedman test χ^2=6, p=0.05; LSD H_{close}>H_{mid} and H_{close}>$H_{distant}$, p<0.05).

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Table 30: Species detected at different distances from I-15 in 2004

DISTANCE FROM ROAD	
Close (50m)	**Distant (400m)**
Peromyscus maniculatus (124) Deer Mouse	*Peromyscus maniculatus* (120) Deer Mouse
Perognathus parvus (39) Great Basin Pocket Mouse	*Perognathus parvus* (54) Great Basin Pocket Mouse
Tamias minimus (27) Least Chipmunk	*Tamias minimus* (18) Least Chipmunk
Dipodomys microps (5) Chisel-Toothed Kangaroo Rat	*Peromyscus boylii* (11) Brush Mouse
Rethrodontomys megalotis (4) Western Harvest Mouse	*Ammospermophilus leucurus* (4)* White Tailed Antelope Squirrel
Peromyscus boylii (3) Brush Mouse	*Rethrodontomys megalotis* (3) Western Harvest Mouse
Neotoma lepida (2) Desert Woodrat	*Peromyscus truei* (2)* Piñon Mouse
Lemmiscus curtatus (1)* Sagebrush Vole	*Neotoma lepida* (1) Desert Woodrat
Spermophilus variegatus (1)* Rock Squirrel	*Dipodomys microps* (1) Chisel-Toothed Kangaroo Rat

Genus, species (# individuals captured), * species found only at these distance classes

Table 31: Species detected at different distances from I-15 in 2005

DISTANCE FROM ROAD		
Close (zero m)	**Mid (200m)**	**Distant (600 m)**
Perognathus parvus (12) Great Basin Pocket Mouse	*Dipodomys microps* (11) Chisel-Toothed Kangaroo Rat	*Dipodomys microps* (2) Chisel-Toothed Kangaroo Rat
Peromyscus maniculatus (10) Deer Mouse	*Perognathus parvus* (4) Great Basin Pocket Mouse	*Perognathus parvus* (2) Great Basin Pocket Mouse
Dipodomys microps (8) Chisel-Toothed Kangaroo Rat	*Peromyscus maniculatus* (1) Deer Mouse	*Peromyscus maniculatus* (1) Deer Mouse
Tamias minimus (2) Least Chipmunk	*Tamias minimus* (1) Least Chipmunk	
Sylvilagus audubonii (2) * Desert cottontail		
Lepus californicus (1) * Jackrabbit		
Neotoma lepida (1) * Desert Woodrat		

Genus, species (# individuals captured), * species found only at these distance classes

Table 32: Values of Shannon-Wiener diversity index (H) estimated for 2004 by transect in Close and Distant webs in Utah

TRANSECT	DIVERSITY INDEX	
	H_{close}	$H_{distant}$
1	0	0
2	0.8	1.27
3	0.8	1.01
4	0	0.3
5	0.35	0.56
6	0.35	1.04
7	1.17	1.3
8	0.43	0.6
9	0.6	0.67
10	0	0.5
11	0.14	0
12	0.99	0.81

Table 33: Values of Shannon-Wiener diversity index (H) estimated for 2005 by transect in Close, Mid and Distant trapping lines in Utah

TRANSECT	DIVERSITY INDEX		
	H_{close}	H_{mid}	$H_{distant}$
1	0.67	0.69	0
2	0.64	0	0
3	1.31	0	0.64
4	1.35	1	0
5	1.04	0.45	0
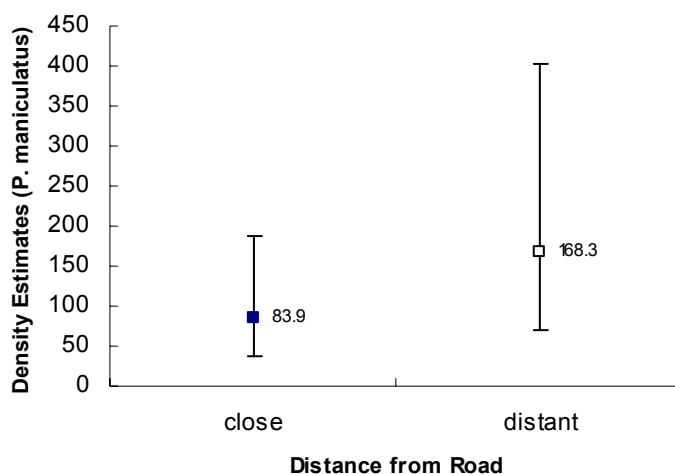
Figure 18: Density estimates of *Peromyscus maniculatus* in 2004 at different distances from the road
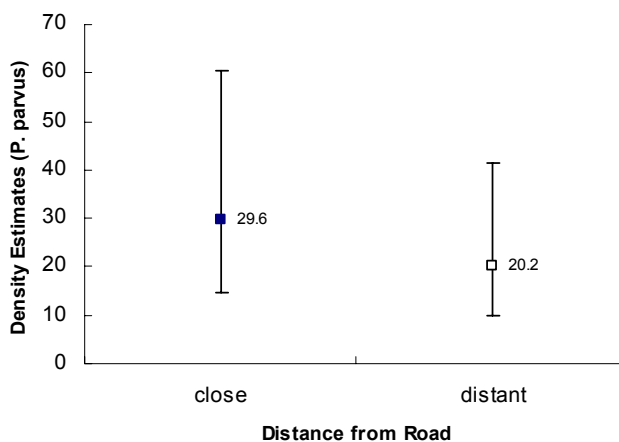
Figure 19: Density estimates of *Perognathus parvus* in 2004 at different distances from the road

For *all* the species in 2004, the overall trend was increased density with increasing distance from the road (Figure 20), however the result was not statistically significant (Wald test Z=-0.49, p=0.63). However, our transects were established along about 20 miles of habitat adjacent to I-15, and we noticed changes in sagebrush habitat, especially in Area B, an area geographically between Areas A and C. Area B had a noticeably different habitat (a distinct sagebrush habitat type), so we conducted the same analysis for all species but segregated the data by three distinct geographic areas. We found different trends in different areas (Figure 21). Densities recorded in area B were significantly greater than in area A for both close (Wald test Z=-2.15, p=0.03) and distant webs (Wald test Z=-3.07, p=0.002), and both were significantly higher than in area C for close (Wald

test Z=-2.84, p=0.004) and distant webs (Wald test Z=-2.97, p=0.003). For 2005, there was a statistically significant trend toward higher abundance near the road (Wald test Z=3.99, p<0.001) than distant from it (Figure 22).
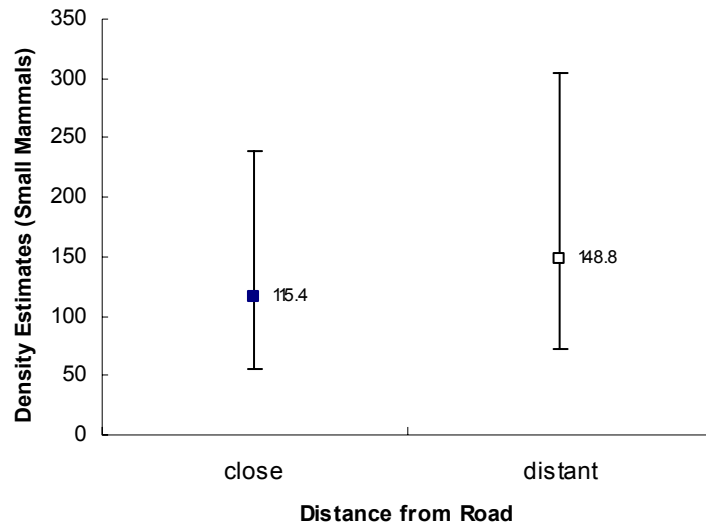
Figure 20: Density estimates of small mammals in 2004 at different distances from the road
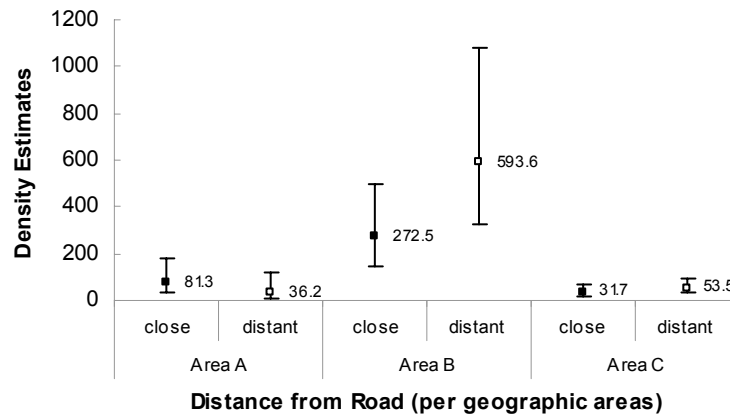
Figure 21: Density estimates of small mammals in 2004 at different distances from the road in three distinct geographic areas (A, B, C).
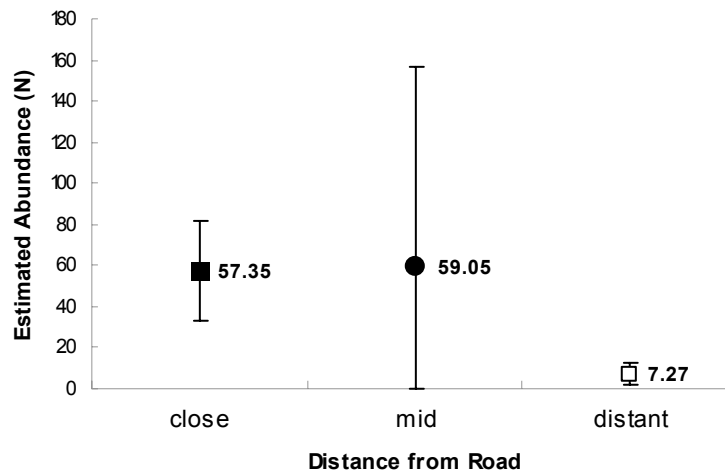
Figure 22: Density estimates of small mammals in 2005 at different distances from the road

British Columbia

We trapped 401 individuals, including nine species of rodents and two species of shrews. Six species were more abundant at highway sites, while five were more abundant at transmission-line sites (Table 35). Five species were present at more highway than transmission line sites and four were present at more transmission-line than highway sites, while the two most common species were present at equal numbers of transmission-line and highway sites (Error! Not a valid bookmark self-reference.). For highway sites, ROW transects had the lowest species diversity (3), compared to the other transects (5-7). Similarly, for transmission- line sites, three species were trapped on ROW transects whereas five to nine species were trapped on the other transects. The low sample sizes and clumpy, among-site distribution of captures prevented within-species comparisons of spatial distribution in relation to transect, with the exception of deer mice (Figure 23).

Table 34). The three most commonly trapped species were deer mice (*Peromyscus maniculatus*), southern red-backed voles (*Clethrionomys gapperi*), and yellow-pine chipmunks (*Tamias amoenus*). True trapping effort was slightly uneven among treatments, sites, and transects due to various trapping impediments that are inherent to field-work in which environmental variables are not always controllable. Trapping problems included several brief but heavy rains snapping traps, larger animals stepping on traps or otherwise snapping them, non-functional traps, usually due to soil thrown up by the impact of raindrops, and a few captures of songbirds which prevented the capture of small mammals. As a result, realized trapping effort was 78% of attempted trapping effort. Capture rates, adjusted for realized trapping effort (Table 35), were low and unevenly distributed spatially for most species. Total capture rates were 9.8 and 12.6 captures per 100 trap-nights, in relation to attempted and realized trapping effort respectively. Six species were more abundant at highway sites, while five were more abundant at transmission-line sites (Table 35). Five species were present at more highway

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than transmission line sites and four were present at more transmission-line than highway sites, while the two most common species were present at equal numbers of transmission-line and highway sites (Error! Not a valid bookmark self-reference.). For highway sites, ROW transects had the lowest species diversity (3), compared to the other transects (5-7). Similarly, for transmission- line sites, three species were trapped on ROW transects whereas five to nine species were trapped on the other transects. The low sample sizes and clumpy, among-site distribution of captures prevented within-species comparisons of spatial distribution in relation to transect, with the exception of deer mice (Figure 23).

Table 34: Small mammal species trapped in British Columbia on transects within 8 highway and 8 transmission-line rights-of-way (ROW), or on transects at varying distances from the ROW centerlines. Data reported as number of individuals trapped and number of sites at which they were trapped (i.e. individuals/sites). Blanks indicate no captures for that species.

Species	Highway					Transmission Line					Grand Total
	In ROW	50 m Out	300 m Out	600 m Out	Hwy Total	In ROW	50 m Out	300 m Out	600 m Out	Tr Ln Total	
Sorex cinereus Common Shrew			1/1		1/1	1/1			1/1	2/2	3/3
Sorex monticolus Dusky Shrew					0/0	2/2				2/2	2/2
Glaucomys sabrinus Northern Flying Squirrel			1/1		1/1					0/0	1/1
Tamias amoenus Yellow-pine Chipmunk	1/1	9/4	3/3	4/2	17/6		3/3	3/1	3/2	9/4	26/10
Clethrionomys gapperi Southern Red-backed Vole		16/2	8/2	9/3	33/3		1/1		10/2	11/3	44/6
Microtus longicaudus Long-tailed Vole			1/1		1/1		3/2	1/1	2/2	6/3	7/4
Microtus pennsylvanicus Meadow Vole	1/1	1/1		3/2	5/3	1/1	1/1			2/1	7/4
Phenacomys intermedius Heather Vole		1/1	2/2	6/5	9/5		2/2	1/1		3/2	12/7
Mus musculus House Mouse		1/1			1/1					0/0	1/1
Peromyscus maniculatus Deer Mouse	28/8	29/6	34/8	35/8	126/8	41/8	29/8	34/7	57/8	161/8	287/16
Zapus princeps Western Jumping Mouse					0/0	7/2	2/1	2/1		11/2	11/2

Table 35: Number of trap nights and trapping results (captures/100 trap-nights) in British Columbia. Traps were considered unavailable for capturing small mammals if they were observed to be snapped without having trapped anything or otherwise not functional during morning checks

Species	Highway					Transmission Line					Grand Total
	In ROW	50 m Out	300 m Out	600 m Out	Hwy Total	In ROW	50 m Out	300 m Out	600 m Out	Tr Ln Total	
Sorex cinereus Common Shrew			1/1		1/1	1/1			1/1	2/2	3/3
Sorex monticolus Dusky Shrew					0/0		2/2			2/2	2/2
Glaucomys sabrinus Northern Flying Squirrel			1/1		1/1					0/0	1/1
Tamias amoenus Yellow-pine Chipmunk	1/1	9/4	3/3	4/2	17/6		3/3	3/1	3/2	9/4	26/10
Clethrionomys gapperi Southern Red-backed Vole		16/2	8/2	9/3	33/3		1/1		10/2	11/3	44/6
Microtus longicaudus Long-tailed Vole			1/1		1/1		3/2	1/1	2/2	6/3	7/4
Microtus pennsylvanicus Meadow Vole	1/1	1/1		3/2	5/3	1/1	1/1			2/1	7/4
Phenacomys intermedius Heather Vole		1/1	2/2	6/5	9/5		2/2	1/1		3/2	12/7
Mus musculus House Mouse		1/1			1/1					0/0	1/1
Peromyscus maniculatus Deer Mouse	28/8	29/6	34/8	35/8	126/8	41/8	29/8	34/7	57/8	161/8	287/16
Zapus princeps Western Jumping Mouse					0/0	7/2	2/1	2/1		11/2	11/2

For this species,there was no difference in capture rate among transects for highway sites (chi-squared P = 0.93) but a difference was realized for transmission-line sites (P = 0.04). Comparing highway to transmission-line sites for each transect, a marginally significant difference was evident between treatments only for the 600m transect (ROW P = 0.32, 50m P = 0.47, 300m P = 0.83, 600m P = 0.05).
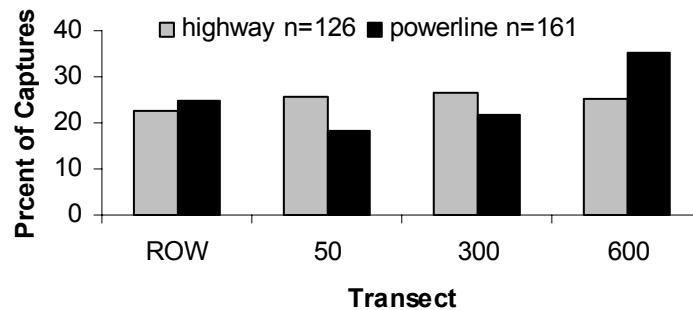
Figure 23: Distribution of deer mouse captures among transects for each treatment. Data adjusted for realized trap effort and non-availability of traps due to the capture of other species

Both for male and female deer mice, animal weights did not differ among transects for highway or transmission-line sites (ANOVA $P > 0.44$ for all comparisons; Figure 24). Comparing highway to transmission-line sites for each sex and transect, no differences in weight were evident (t-test $P > 0.24$ for all comparisons) with the possible exception of males on the 600m transect ($P = 0.06$).

There was no difference in sex ratio among transects for highway sites (chi-squared $P = 0.88$), but there was some evidence of a difference among transects for transmission-line sites ($P = 0.07$; Figure 25). Comparing highway to transmission-line sites for each transect, there was weak evidence of a difference between treatments only for the 600m transect (ROW $P = 0.92$, 50m $P = 0.79$, 300m $P = 0.32$, 600m $P = 0.09$).

Juvenile:adult ratios did not vary significantly among transects for either treatment, or among transect for any treatment (chi-squared $P > 0.17$ for all comparisons except highway vs. transmission line for ROW transect, for which $P = 0.08$; Figure 26). Sample sizes were relatively low, likely due to a combination of a low realized trapping effort, some periods of inclement weather that may have limited animal activity and survivorship, and the timing of sampling effort. Our field season occurred early in the summer when recovery from the annual winter population decline would have been incomplete for some species.[224] Combining all transects per site, similar patterns of diversity and abundance were evident between transmission-line and highway sites, although, distribution was clumpy for most species. With the exception of deer mice and
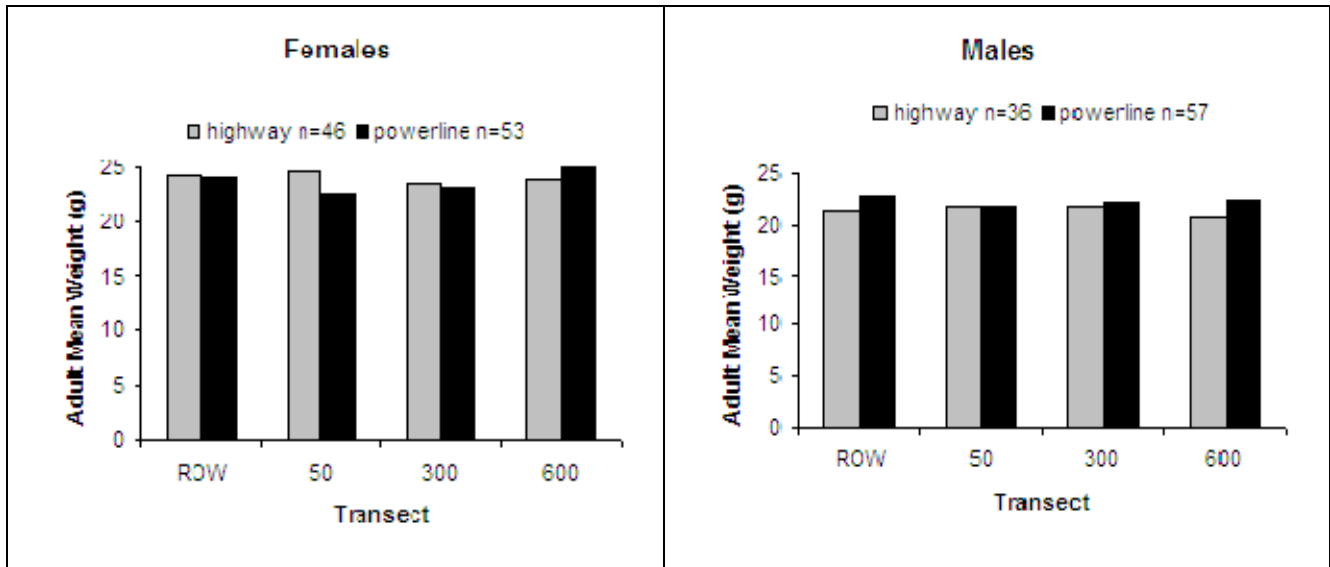
Figure 24: Weights of adult deer mice, compared among transects for each treatment
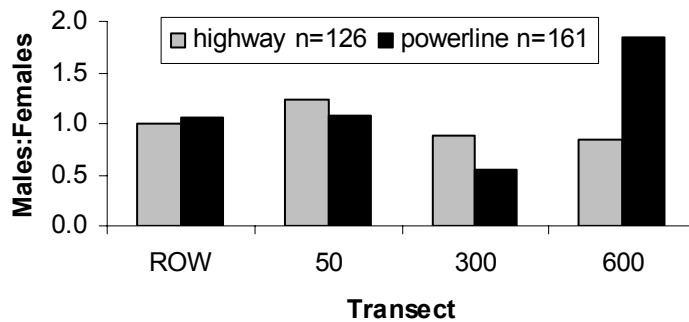
Figure 25: Sex ratios of deer mice, compared among transects for each treatment

yellow-pine chipmunks, each species occurred at fewer than half of the sites, despite being common at some of those sites. For any given transect distance, only deer mice were trapped at more than half of the sites. This clumping suggests that within the forest, microhabitat or some other localized effect was stronger than any influence of distance to the highway.

Species diversity was lowest in ROW transects than any other transect. However, there is no strong evidence to suggest that this observation was related to anything beyond a shift from native forest at 50, 300, and 600m transects, to the less complex structure and vegetation of the disturbed habitat in the ROW. For example, optimal

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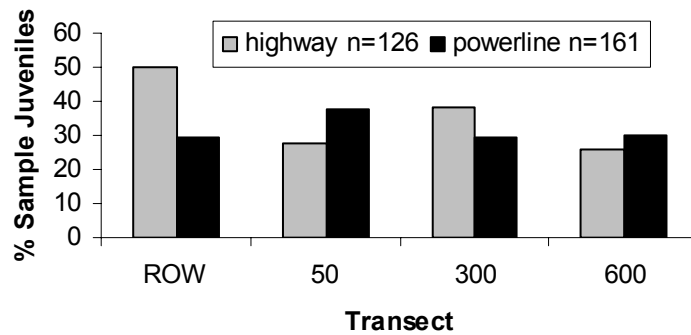
Figure 26: Juveniles as a percentage of total deer mouse sample, compared among transects for each treatment

habitat for yellow-pine chipmunks appears to be open forest with abundant woody debris, southern red-backed voles are most common in mature forests with abundant shrub and ground cover, heather voles are associated with a dense shrub layer and abundant woody debris, and in the dry interior of British Columbia (where our study area was located), long-tailed voles are associated with shrub thickets.[178] Thus, it is expected that ROWs with no forest or downed woody debris, and few shrubs would have fewer of these species, independent of the presence of a highway nearby. The only species trapped more often on ROW transects was the western jumping mouse, consistent with its preferred habitats which are more typically associated with ROWs than forest (i.e. rich meadows with abundant forbs.[178] Had there been a strong effect of highway proximity, there should have been differences between the highway and transmission-line sites for the ROW transects. In fact, no species were more common in the transmission-line ROW than the highway ROW with the exception of aforementioned western jumping mice. They were found at only two sites which were separated by 1.5km. Interestingly no presence was detected at a site between the two, which appeared to be largely identical habitat. This suggests a strongly uneven distribution, and the likelihood that the greater abundance at the transmission-line sites was a chance effect.

Deer mice provide a better opportunity to compare transmission-line ROW to highway ROW transects, given this species employs very broad habitat-use patterns and distribution.[178] It was also typically abundant in our samples. There were no observed differences between transmission-line and highway ROW samples for deer mouse abundance, sex ratio, and male weight or female weight. There was, however, a weak suggestion of a greater proportion of juveniles in the sample on the highway site. The latter observation could be taken to be indicative of a highway effect, with juveniles perhaps being displaced to lower-quality habitat or alternatively having higher survivorship. Still, there was evidence of differences among treatments at the 600m transect for deer mouse abundance, as well as male weight and sex ratio. It would be extremely unlikely that a highway effect would be evident at the 600m transect without being obvious at the 300m, 50m and ROW transects. This suggests a high likelihood of any differences between treatments in deer mouse variables, being related at least as

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much to chance, microhabitat, or other localized effects, as to the presence of the highway.

Adams and Geis[2] conducted similar research in the southeastern, midwestern, and northwestern United States. Their results also suggest that the effect of road proximity differs by species. In the case of deer mice (and converting to absolute numbers the percentage composition they report), abundance was consistently higher near interstate than county highways. It is not clear that this relates to the larger area of grassy habitat along interstate highways, but does suggest that large highway size and volume did not have an overwhelmingly negative effect on deer mice. In keeping with that observation, the authors found no consistent regional patterns of deer mouse abundance in relation to distance from highway, whether comparing the ROW to sites 80-160m and 240-320m from it, or in combining the latter 2 sampling distances. The only other species reported by Adams and Geis[2] that had more than one capture in our study was the meadow vole, for which there was a broad tendency to be more common closer to roads, but no consistent pattern with respect to highway size. Geographically closer to our study area, was the field site of Mills and Conrey[170] in northwestern Montana. In forested habitat adjacent to the ROW of two, 2-lane highways, southern red-backed vole abundance was greater on a trapping grid close to the highway at one site but greater on a grid distant from the highway at the other site. Deer mice and chipmunks (combining yellow-pine chipmunks and red-tailed chipmunks, *Tamias ruficaudis*) appeared to be marginally more abundant on the grids nearest to the highways. At a site along a 4-lane highway, rodent abundance on a trapping grid straddling the ROW-forest boundary was compared to a second grid farther from the highway and entirely in the forest. In that case, deer mice were more abundant near the highway whereas red-backed voles and chipmunks were most abundant farther from the highway. Those results are consistent with a simple preference for open habitats by deer mice, and for forest by red-backed voles and chipmunks, which is consistent with our results.

Interpretation, Appraisal, and Applications

In Utah, we recorded higher abundance and density further from the road in 2004, and higher diversity and abundance closer to the road in 2005. These conflicting trends suggest that roads per se do not have a direct effect on small mammal distribution. Other factors clearly have a more decisive influence. The presence of suitable habitat and resource availability seem to be primarily influenced by abundance and density. Desert habitat quality is very often dependent on precipitation levels, which were very different in 2004 (wet) and 2005 (dry). In 2004, the general habitat quality appeared to be good throughout the range. In contrast, during a drier year such as 2005, green vegetation and suitable habitat appeared to be limited to areas adjacent to the road, which may have acted as a water collector, and perhaps responsible for the higher concentration of individuals and species near the road.

Similarly in British Columbia, there was no consistent patterns to indicate small mammal abundance or densities changed consistently within the forest as distance from the ROW increased. If there were demonstrated demographic effects caused by this relatively low-volume, 2-lane highway other than those due to the simple shift in habitat type from forest to graminoid (grass) cover in the ROW, they were less evident than were

the effects of site or microhabitat conditions in the ROW. Similarly, the 60m wide highway or transmission-line ROWs that dissected mesic coniferous forest, appeared to be negative for most species and potentially neutral to positive for others, with total species diversity lower in the ROW than forest. This is not to suggest that impacts due to the highway itself may not exist for some species, but that large samples and highly consistent habitat conditions would be required to detect them.

Conclusions

Jaeger et al.[133] suggested four ways that roads might influence the persistence of animal populations. One important parameter includes a decrease in habitat amount and quality near roads. If habitat quality decreases, one would expect that the animals that inhabit areas near roads would decrease in diversity, density, and/or abundance. Our results from the dry, arid Intermountain West sagebrush country of Utah to the mesic, coniferous forests of southern British Columbia found no consistent patterns to suggest that habitat quality differed beyond the ROW verge. We found no consistent pattern that small mammals were impacted close to the road, and conclude that at least on our study sites, roads did not impact habitat quality beyond the ROW. We suggest other factors may be responsible for the differences in small mammal species diversity, density, and abundance that we documented.

RESTORING HABITAT NETWORKS WITH ALLOMETRICALLY-SCALED WILDLIFE CROSSINGS (3.5)

Lead:

J. A. Bissonette

Abstract

The allometric relationship between dispersal distances and home range size of mammalian species can be used as an important first step in deciding on the placement of wildlife crossing structures that will help restore landscape permeability across fragmented habitat networks. Roads have disrupted habitat networks; i.e., the natural interconnectedness of heterogeneous and patchy landscapes, and as a consequence, changed normal animal movement patterns across the landscape. There have been useful developments in allometric scaling laws that have led to important and statistically sound relationships between home range size and dispersal distance for species. The recently described implications of the relationship of median dispersal distance (MedDD) to home range area, and the development of a single metric, termed the Linear Home Range distance (LHRD) to represent home range size, provide scaling laws that can be related to the concepts of ecological neighborhoods and domains of scale to consider how the movement of species guilds with similar movement capabilities can be enhanced by effective placement of crossing structures in roaded landscapes. In turn, this will reduce fragmentation effects and improve permeability across habitat networks. It is possible to use MedDD ($7 * \sqrt{\text{Home Range}}$) as the upper bound, and a LHRD ($\sqrt{\text{Home Range}}$) as the lower bound to develop alternative domains of scale for groups of animals to guide the placement of wildlife crossings. With additional information regarding hot spots of wildlife-vehicle colllisions as well as dead animal counts on roads, the placement of wildlife crossings, along with appropriate auxiliary mitigation such as exclusion fences and right-of-way escape structures, should significantly improve road safety as well as provide for easier movement across the roaded landscape.

Introduction

The placement of crossing structures has been a relatively hit-and-miss proposition lacking solid ecological theory to underpin the decision, in part because the idea of landscape permeability has not been traditionally viewed from an animal perspective. By permeability, I refer here specifically to the ability of species of all kinds to move relatively freely across the roaded landscape. By my definition, landscape permeability differs from the term connectivity. Connectivity as I define it here refers to the human perception of how connected the landscape matrix is, irrespective of organism scaling. Permeability implies free movement by organisms across the landscape. Stevens et al.'s [223] use of the term 'functional connectivity' (i.e., the ability of an animal to cross a landscape) is roughly equivalent to my definition of permeability, but relies on the concept of relative resistance of matrix habitat separating habitat patches. Relative resistance refers generically to the degree to which boundary conditions between habitats as well as habitat physical structure allow or impede animal movement. Animal vagility

(i.e., the capacity or tendency of an organism or a species to move about or disperse in a given environment) differs from species to species, and with age and sex class in many species. An animal's movement capabilities define in large part its abilities to find resources necessary for survival. The development of allometric equations that relate the home range sizes of species to movement ability allows one to calculate scaling properties for individual species. Allometry is a fundamental concept in biology. It is the relation between the size of an organism and the size of any of its parts; for example, between brain size and body size, where animals with bigger bodies have bigger brains.

Here I refer to the relationships between home range size and different measures of movement ability (MedDD, LHRD) as allometric because they have consistent scaling properties that can be expressed by equations. Scaling properties can be translated into movement distances characteristic of a species. Movements of animals over time can be referred to as their ecological neighborhood; i.e., a region defined by an animal's movement pattern. Ecological neighborhoods for any individual species vary depending upon which process is involved. For example, while foraging, movement distances typically are relatively short, migratory movements involve larger ecological neighborhoods. Animals of similar size tend to have similarly sized home ranges and ecological neighborhoods. When this is so, it is possible to establish scaling domains that include a few to many species. For the purposes of this paper, a scale domain refers to a range of species movement distances that are similar, so that several species can be considered to belong to that particular domain. Domains range from small to large, typically with more sedentary animals belonging to a domain characterized by short movement distances and highly vagile animals belong to a domain characterized by longer movement distances. To the extent that species belonging to a specific domain move similarly, the placement of wildlife crossings of appropriate type and configuration at appropriate (allometric) distances will promote landscape permeability. Less vagile animals need crossings placed closer together, while for more vagile animals wildlife crossings can be spaced further apart. The advantage of domains is that often, a single crossing can be used by many different types of species. There are obvious advantages for both population viability and driver safety when species use crossings and stay off the road surface. Mitigation to decrease the effects of the roaded landscape includes, among other things, the construction of crossing structures of two general types; those that cross over the road, and those that provide passage underneath. The number, type, configuration, and placement of crossing structures will determine whether permeability is restored to the roaded landscape. The relevant hypothesis is that landscape permeability can be improved by the placement of crossing structures allometrically scaled to organism movement characteristics.

Research Approach: Methods and Data

The roaded landscape has both direct (road kill, habitat loss, fragmentation) and indirect (barrier, loss of connectivity, reduced permeability) effects on wildlife populations and on ecological patterns and processes.[26,30] In particular, animal <u>movement</u> is hindered as road density increases. Spatial linkage, accomplished by animal movement, is critical because the array of resources that are essential to population viability are usually distributed heterogeneously across the habitat network.[168] Animal movement can be seasonal migrations[120] that tend to be cyclic, dispersal events[226] that are usually

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unidirectional[180], or ranging behavior[144,227,216] characterized by shorter exploratory movement within a home range or territory. Regardless, the ability of animals to move has profound impacts on ecological phenomena and processes, including individual fitness, population structure, life history strategies, foraging dynamics, and species diversity.[3,33] Generically, dispersal has been defined as the movement of organisms, their propagules, or their genes away from the source.[222,233,59,179,38] Although this study explores the patterns of dispersal distances to understand the placement of wildlife crossing structures, clearly the processes involved in dispersal underpin our ecological understanding. The phenomena of immigration and emigration, collectively termed dispersal, are two of four (births, deaths being the other two) processes that are the least understood in the fields of population ecology and life history evolution,[75] and represent one of the most significant gaps in how ecologists understand animal ecology.[22] Wiens[245] has argued that dispersal is a complex process that involves more than just patterns of where animals settle. According to Doerr and Doerr[75] a more comprehensive view of dispersal is emerging. Clobert et al.[59] have argued recently that at least three components are involved in dispersal: a) a decision to leave the natal area, b) a middle phase where new areas are searched and evaluated, and c) a final phase that involves choosing a place to settle. This view suggests that dispersal distances result from this integrated series of decisions and processes and are influenced by environmental and physiological factors, as well as stochastic events.[75] Perhaps most critical to our understanding is a dearth of data regarding these processes. For this report, we consider dispersal to be at the level of individuals and populations. Although barrier effects are not similar across roads, the effects of road geometrics (road type, width, presence of fences) present significant problems to animals, resulting in fragmented habitats, disconnected networks, non-permeable or semi-permeable landscapes[26] and often isolated populations.[43,239,137]

A Brief History of Allometric Scaling in Ecology

Allometric scaling in ecology has had a long history. It is not my intention to cover the history exhaustively, but only to indicate the line of logic that led to these analyses. As early as 1909, Seaton[209] recognized that animal size corresponded roughly with home range size. Mohr[174] discussed the same relationship specifically for mammalian species. Kleiber[141] looked at the scaling relationships between basal metabolic rate (BMR) and body mass and found that (BMR = aM$^{0.75}$), where M is body mass, a is the allometric coefficient (Y intercept), and 0.75 is the allometric scaling exponent. The general form of the allometric (power law) scaling equation is:

$$Y = aX^b$$

where Y is the response variable, X is the explanatory variable, a is a scaling constant or coefficient (y intercept), and b is the scaling exponent equal to the regression slope.[141,147] McNab[165] showed that among mammals, an almost identical power law (scaling exponent) existed between home range size (HR) and body weight, although Harestad and Bunnell[112] found scaling exponent values near 1.0 or greater when they looked at different trophic levels. They concluded that differences in weight alone accounted for a large proportion of the differences between male and female or subadult and adult home range sizes. They suggested that inter-trophic (namely, herbivores vs. carnivores vs. omnivores) scaling functions differed significantly from each other. Damuth[68] and

Brown[37] have suggested that the difference between the scaling exponents of 0.75 for energy requirements and ~1.0 for home range size may be explained by per capita resource requirements and greater overlap in home ranges for larger mammals. However, more recent work by Kelt and Van Vuren[139], working from a large data base of over 700 publications, found that the scaling relations of inter-trophic home ranges did not differ and scaled with a slope of 1.13, greater than either the results of McNab[165] or Harestad and Bunnell[112]. Kelt and Van Vuren[139] (p. 637) admit however that the relationship between home range size and body mass "has been perhaps the most difficult to understand." Recently, Wolff[247] and Sutherland et al.[226] demonstrated that body size of mammals is linearly related to dispersal distance when both variables were expressed on a $\log_{10}$ scale. However, as Bowman et al.[33] point out, both of these relationships are limited because: a) some species disperse much further than expected from body size, and b) some mammals have larger or smaller home ranges than predicted for a given body size. Given these results, one expects that home range size and dispersal distance should co-vary across mammalian species and this is the argument that Bowman et al.[33] expand upon. They argue that the <u>residual variance</u> in the body size vs. home range, and the body size vs. dispersal distance relationships represent real differences in vagility independent of body size and therefore the relationship between dispersal distance and home range size should co-vary across mammal species after the effects of body size are removed.

The Dispersal Distance Connection

Dispersal is a fundamental element of demography[7], colonization[117], and gene flow[182] but dispersal movements are perhaps the least well understood of ecological phenomena.[226] Bowman et al.[33] showed that dispersal distance is actually more closely related to home range size ($R^2 = 0.74$) than to body size ($R^2 = 0.60$), where R^2 is the proportion of the variance explained by home range size and body size, respectively. This is a significant discovery because dispersal distances, as well as ranging and migratory behavior, represent animal movement across the landscape. Bowman et al.[33] found that when body size effects were removed, the slope of the relationship of the residuals of dispersal distance regressed against the residuals of home range size was not significantly different from 0.50 (F = 31.6, df = 1, 32, P = 3.2 x 10^{-6}, S.E.E. = 0.54), a result with very important ramifications. The significance is this:

> Dispersal distance is a linear measure, while home range area is a squared linear measure. Because $X^{0.05}$ is equal to $\sqrt{X}$, and because X in the scaling equation is equal to home range area, taking the square root of the home range area yields a <u>linear</u> dimension of home range, allowing dispersal distance to be related to home range size by a single constant value.

Bowman et al.[33] found that maximum dispersal distance (Max DD) was related to home range size (HR) by the equation:

> MaxDD = 40 (linear dimension of home range); and median dispersal distance (MedDD) by the equation: MedDD = 7 (linear dimension of HR)

Because home range size is easy to measure and is readily available in published literature, appropriate scaling functions for deciding the general ecological neighborhood

of species would appear to be easy to obtain. If so, they provide the next step to inform the placement of wildlife crossing structures.

What is an Ecological Neighborhood?

The concept of ecological neighborhoods is defined by three properties: a) an ecological process (e.g., inter-patch movement); b) a time scale relevant to the process; and c) an organism's activity during that time period.[3] Additionally, <u>no single temporal or spatial scale</u> is appropriate to represent the mix of processes that influence individual and species responses through time and space, hence several ecological neighborhoods exist, depending upon what process is involved (e.g., foraging, territory defense, migration). Characteristically, for mobile organisms, the ecological neighborhood for a <u>given</u> process is the region within which that organism is active, definable by its movement patterns. Indeed, Addicott et al.[3] (p. 343) suggest that "for neighborhoods…. the most appropriate indicator of activity may be a measure of net movement of individuals…. One *(such indicator)* is the direct measurement of dispersal distances."

Figure 27 shows the theoretical relationship between movement and two ecological neighborhoods where N_1 and N_2 represent two different spatial units related to two distinct animal activities. The horizontal and vertical dashed lines indicate different 'neighborhood sizes' for the two different activities (dotted curves, Figure 27A). In general, if we think about landscape permeability, larger spatial units are involved. In this example, foraging involves a smaller ecological neighborhood (N_1), but inter-patch movements, which might include finding mates or additional resources, typically involves larger spatial areas (N_2), i.e., larger ecological neighborhoods and may be equated with some measure of dispersal.

When roads cross the landscape, the larger ecological neighborhoods that animals use may be intersected. When this occurs, barrier effects become apparent. In Figure 27, both inter-patch interactions involving movement over large distances and the movements related to the shorter foraging activities are defined by a cumulative distribution of distances moved. The decision criteria is 95% of all movements related to either process[3], but is arbitrary; it could easily be different.Given the results from Bowman et al.[33], the problem of deciding an appropriate spacing for wildlife crossings is now somewhat easier because we can relate ecological neighborhoods of activity required by animals to survive to distance. Usually, ecological neighborhoods are defined for each individual species. However, it is unreasonable from a management perspective to attempt to place crossing structures allometrically for each individual species. Some grouping of species is desirable, especially if their home range sizes are similar in size and have small <u>among</u> vs. <u>between</u> differences.
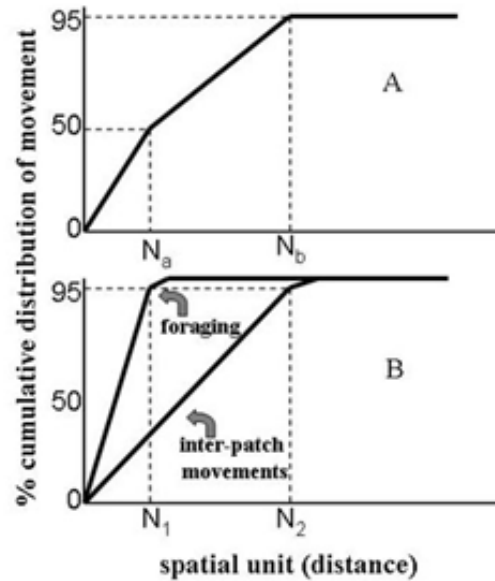
Figure 27: Theoretical relationship between the cumulative distribution of organism movement and spatial scale, i.e., ecological neighborhood (A). Each curve in (B) represents a cumulative distribution of movements with an associated neighborhood size (N_1, N_2) for foraging and inter-patch movements. Redrawn from Addicott et al.[3]

Domains of Scale

To the extent that: a) similarities in home range sizes exist for groups or guilds of species; and b) there are recognizable differences between groups, it should be possible to determine a few effective scale domains that characterize the movements of each group. Theoretically, boundaries of scale domains should be recognized where the differences (e.g., in dispersal distances) increase as transitions between domains are approached. If possible, then the recognition of a few groups or guilds comprised of similarly sized species with similar home range domains is an important first step in determining the spatial location for effective crossing structures for most species. The assumption is that similarly-sized animals will use similar types and similarly-spaced crossing structures. However, there may be inter-trophic differences (i.e., carnivores, herbivores, and omnivores may scale differently). If so, consideration should be given when deciding on the type and placement of wildlife crossing. The calculation of guild-specific movement domains is an important step in allometrically placing wildlife crossings. To the extent that these arguments hold, the placement of appropriate types of crossing structures can be accomplished in a scale-informed and sensitive manner, resulting in a more permeable roaded landscape that effectively restores the broader habitat network.

Wildlife Crossings and Inter-patch Movements

The intent, of course, of establishing allometrically-scaled wildlife road crossings is to enhance inter-patch movements. Most if not all organisms live in discontinuous habitat patches of suitable habitat within a matrix of less suitable habitat that is embedded

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in larger, naturally heterogeneous landscapes,[34] and the presence of roads generally increases patch isolation. Ecologically, animal vagility and movement ability determine if populations are isolated in a naturally heterogeneous landscape.[3,34] Although important, inter-patch movement has not been extensively studied and few empirical estimates of movement rates… . or effects on … . populations have been derived"[34]. It is unclear what amount of inter-patch movement is needed to influence the dynamics of populations divided by roads. While real problems exist in gathering inter-patch movement data [34] , Bowne and Brown [34] conducted a database search to determine the extent that documented rates were available.

From a review of 415 published articles, they found that for 89 species-system combinations, roughly 15% of all individuals in a population moved between habitat patches each generation. More importantly, population effects (i.e., birth rates, death rates, recruitment, survival) were either positive (n = 28) or neutral (n = 14) over 95% of the time, but negative in only two instances (<5%). This finding underscores the necessity of restoring functional connectivity to the roaded landscape. Inter-patch movements may involve relative short distances or long distance dispersal. Shorter movements are more frequent, while longer dispersal distances are typically rare.[231]

Description of Methods

Bowman et al.[33] developed their home range dispersal relationships for mammals from data given in Harestad and Bunnel.[112] I used the Harestad and Bunnell[112] data and augmented those with the species home range list given in Holling[122] Appendix 7, to amass a total of 103 species from around the world (Appendix G). Other sources of home range data are available, but the Harestad and Bunnel[112] data are well-known, accepted by ecologists, and are the data that have been used to advance the allometric scaling of mammals.[139] The Holling[122] data increased the number of species for which reliable home range data are available. Only data for species with at least five replicates were used in the Holling data. Some species do not occur in North America, but were included because: 1) the data related to their home range areas were reliable, and 2) they provided a reasonable sample size from which to develop reliable dispersal distance domains. Elimination of duplicate entries left 103 species. A caveat is necessary here. Home range size varies over time for individuals and for populations. The values used in this study are the best representative values available for the species. Individual home ranges will no doubt vary around these mean values. I then used the Bowman et al.[33] equations to calculate median dispersal distances (MedDD; i.e., $7* \sqrt{HR}$, and linear home range distances (LHRD, i.e., $\sqrt{HR}$) from these home range data, and data from 10 papers that listed daily movement distances (DMD) to explore if there was a consistent relationship between DMD and the MedDD. If there is, then three different scaling domains could be developed to inform the placement of crossing structures. All three transformations (MedDD, LHRD, and DMD) represent different ecological neighborhoods for individual species. After the distance conversions were calculated, I used a hierarchical monothetic agglomerative clustering technique using Ward's linkage method with a Euclidean distance measure as the sorting strategy[162] to detect natural breaks in the data. Monothetic refers to the clustering of one variable (i.e., the measure of home range), agglomerative refers to the procedure of clustering groups of species and means such that each group starts as a single species and are clustered (agglomerated) by some linkage method. I

used Euclidean Distance because it is one of the simplest measures and is roughly equivalent to the linear distance between any two measures. The shorter the distance, the more similar the measures and the more likely the species involved will be included in a group. Ward's method is based on minimizing the sum of the squares of distances from each individual species to the centroid of its group.[161] The method produces a clustering matrix and a dendrogrm of the species groups. I chose to represent the data to the sixth cluster (i.e., to the 0.16 mile level). After the natural breaks were detected, I used them to calculate frequency distributions for the species home range areas that had been converted to the median dispersal distances and to the linear home range distances. The frequency distributions are equivalent to scale domains that represent similar scaling by groups of species. I also compared trophic level (i.e., carnivore, herbivore, and omnivore) median dispersal distances to determine if differences existed. I looked at a sample of 10 papers that provided daily movement data and examined if there was a consistent relationship between daily movement distances and median dispersal distance. Because median dispersal distance and linear home range distances are derived from home range area, if there was a relationship, it should apply to any of these measures. Finally, I compare the options for spacing wildlife crossings and present the most feasible scaling domains for large mammals that are most likely to be involved in serious animal vehicle crashes.

Findings and Results

Mammalian Species Scaling-Median Dispersal Distance

When we used the median dispersal distance equation (7 * √ Home Range) mammalian species distances ranged from 0.06 miles (northern pocket gopher *Thomomys talpoides*) to 168.46 for wolverine (*Gulo gulo*). Of 103 species, 50% scaled to less than
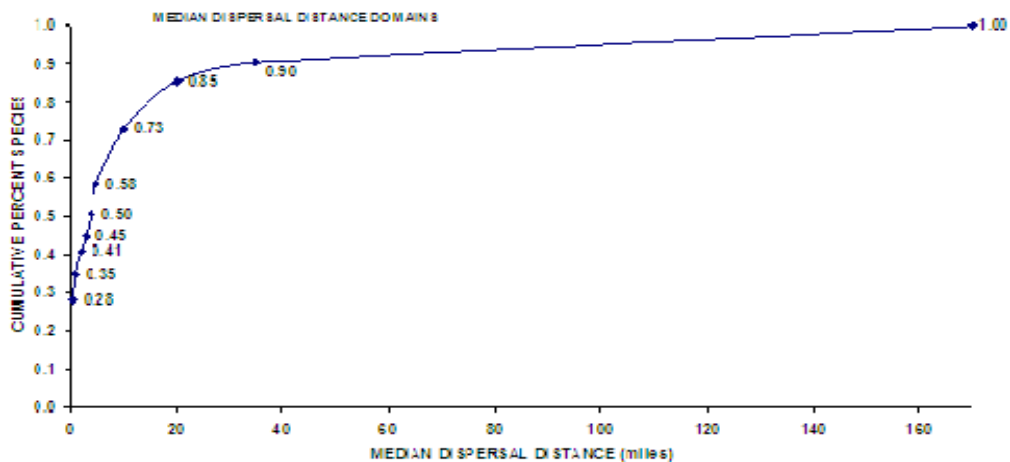
Figure 28: Median dispersal distances of 103 mammalian species with no clustering

4 miles (Figure 28, Table 36). More than 70% of species had median dispersal distances of 8 miles or less. When median dispersal distances were grouped by a hierarchical

polythetic agglomerative clustering technique[162], 55.4% scaled longer than 3.05 miles (Figure 29).

Table 36: Cumulative percent of mammalian species that scale at distances from 0.5 to >35 miles

Med DD (miles)	0.5[*]	1.0	2.0	3.0	4.0	6.0	8.0	20.0	35.0	>35.0
Cumulative%	28.2	35.0	40.8	44.7	50.5	63.2	70.9	85.4	90.3	100

[*]mile value given is upper limit for that distance domain

Not all trophic levels (i.e., carnivores, herbivores, and omnivores) scale similarly. One expects that carnivores, whose prey is the herbivore component of the community, would travel greater distances and have larger home ranges. Similarly, herbivores whose primary food resource includes plants, would be expected to scale differently and indeed that is the case. Indeed, MedDD for omnivores ranged from 0.39 -50.05 miles, herbivores ranged from 0.06 to 16.47 miles, and carnivores from 0.14 to 168.46 miles (Figure 30 and Figure 31). It is clear that wildlife crossings placed 6 or more miles apart will not provide either permeability or adequate crossing opportunities for ~63% of the species likely to be found on the landscape. Clearly median dispersal distances provide only the extreme limit and by themselves cannot fully inform the placement of crossing structures.
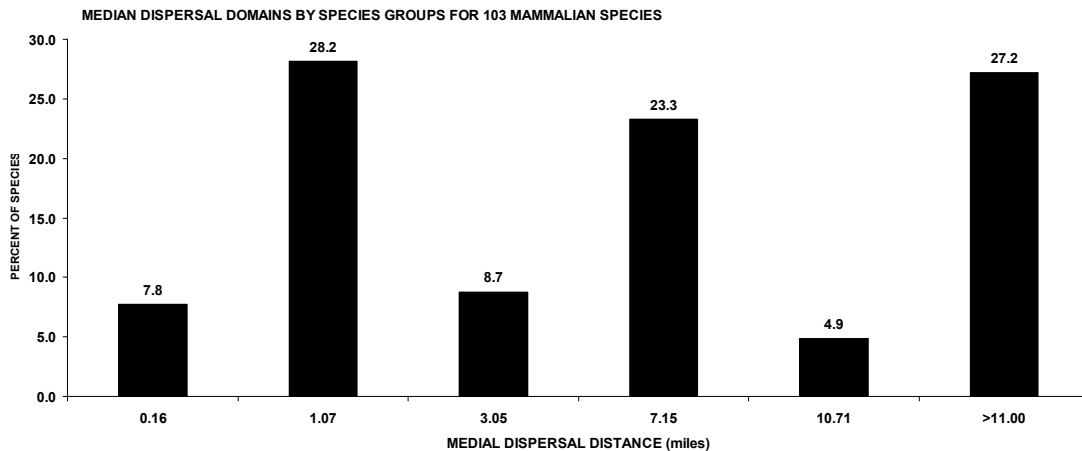
Figure 29: Median dispersal (7 * √ Home Range) domains for 103 mammalian species based on a hierarchical polythetic agglomerative clustering at GMV6. X-axis values represent the upper boundary of the particular domain

Mammalian Species Scaling-Linear Dimension Distance

At the other end of the spectrum, the linear dimension of the home range (√HR) provides a scaling that more closely approximates the majority of movements made by mammalian species, which typically move within their home range for most of the year.

During spring and fall of course, juvenile animals[176] usually make longer migratory movements. When linear movement domains are used to place multiple wildlife crossings according to the spacing shown in Figure 32 (i.e., at 0.5, 1, 1.5, 3.0, and 4.0 miles) 2.9% of species would be likely to cross at distances of 4 miles, 16.5% would cross at 3.0 miles, 22.3% at 1.5 miles, 41.7% at 1.0 mile, and 89.3 % of all species could cross at ≤0.5 miles. Consequently, maximum landscape permeability is more likely when placing wildlife crossings based on the linear scale domains.

Mammalian Species Scaling-Daily Movement Distance

It is possible that daily dispersal distances may provide an alternate scenario for placing wildlife crossings, however daily movement distances are difficult to collect and often not uniformly collected. For example, Krausman et al. (unpublished data) collected movement data on 46 mule deer (*Odocoileus hemionus*) whose movements were followed using radio telemetry from 1999-2003 (Figure 33). Recording of the relocations occurred at about 24 hours intervals. The data indicate that the majority of individual daily movements were short with 85.1% being 1000 meters or less.
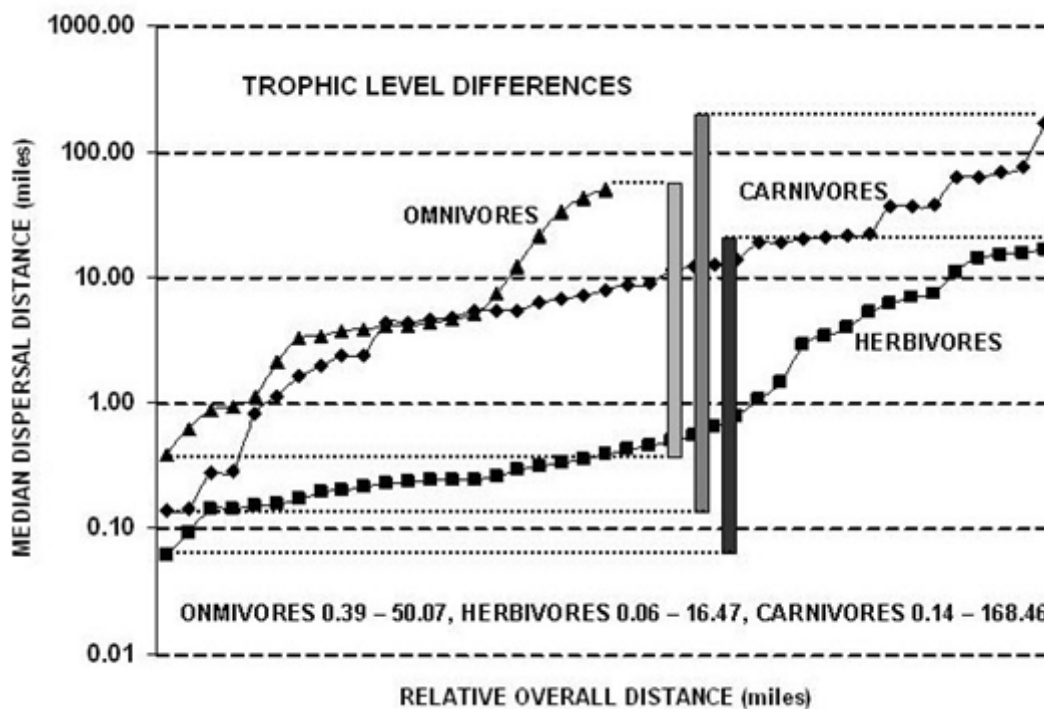
Figure 30: Carnivores, herbivores, and omnivores show different median dispersal distances

Certainly deer moved greater distances, however taking two locations, one at the beginning of the period and one at the end, essentially straightens what is a much more tortuous movement pathway. This is the major problem of using daily movement data. The most accurate method for assessing daily movement distances would measure the trajectory of the animal's pathway at short intervals for several 24-hour periods using

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Global Position System (GPS) collars set to record locations frequently, and then taking a mean value. Seasonality affects daily movement patterns, so an adequate sample is needed. Typical methods for collecting daily movement distance data include following the trajectory for a few hours and then extrapolating daily movement distance, or taking only a few (often as few as two) telemetry relocations over a 24 hour period and then measuring the straight line distance between relocations. This seriously underestimates daily movement distances.

COMPARISON OF TROPHIC MEDIAN DISPERSAL DISTANCES
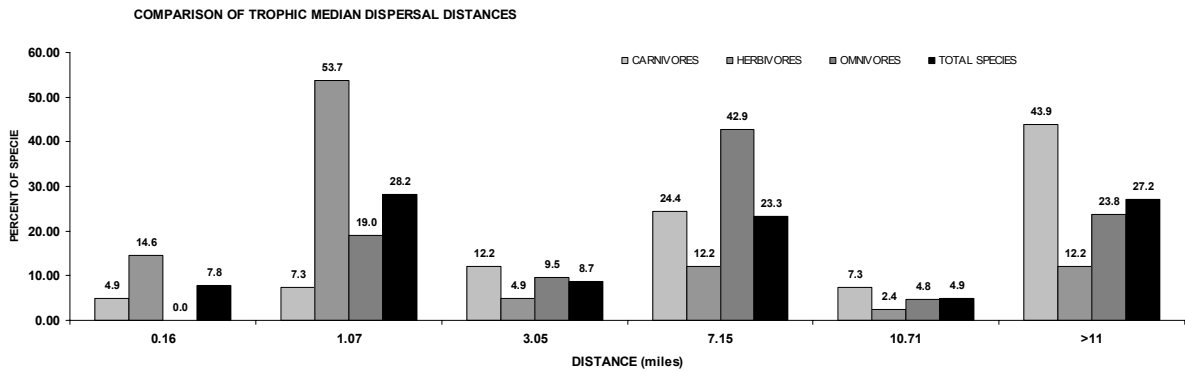
Figure 31: Comparison of the median dispersal distance domains of carnivores, herbivores, and omnivores

HIERARCHICAL MONOTHETIC AGGLOMERATIVE CLUSTERING
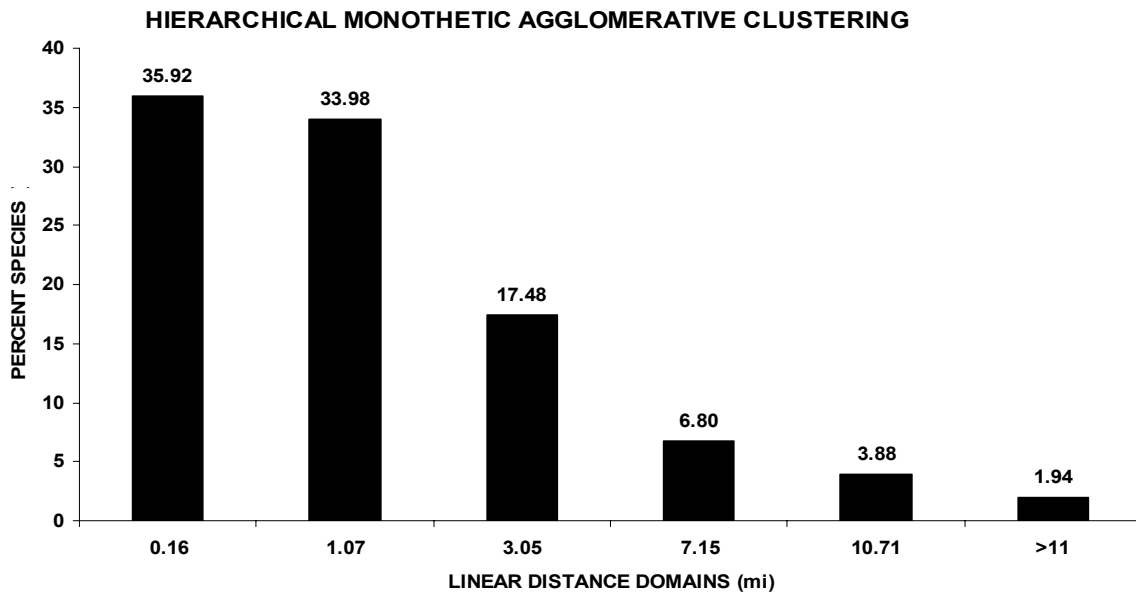
Figure 32: Linear (√ Home Range) dispersal domains for 103 mammalian species using hierarchical polythetic agglomerative clustering

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However, if there is a consistent relationship between daily movement distances and median dispersal distance, with properly collected data (e.g., by using continuously monitoring GPS radio transmitting collars), a conversion factor can be developed for daily movement distance domains that might help inform wildlife crossing distance. I initially found 10 species for which daily movement data were available (Table 37). As can be seen, the relationship between median dispersal distance and daily movement distance for all ten species is quite loose, with a mean of 61.95, s.d. = 83.62, P = 0.05. Mean values for carnivores alone = 42.66, s.d. = 84.45, P = 0.05, and for herbivores, mean = 96.4, s.d. = 93.27, P. =0.05. The variation of the ratios between the median dispersal and daily movement distances is too large to give a realistic and reasonable conversion factor. With a larger sample, the results might be different. Alternatively, if accurate multiple daily movement distance estimates are available for those large species that account for the greatest safety risk when wildlife vehicle collisions occur, then a proper daily movement distance scaling can be developed for individual species. Additional work will be necessary to see if those data exist.

Table 37: Daily movement distances for 10 mammalian species

SPECIES	TL[1]	MED DD[2] (m)	DMD[3] (m)	Ratio
swift fox (*Vulpes velox*)[4]	C	19712	18500	1.07
European marten (*Martes martes*)[5]	C	8573	5100	1.68
Eurasian lynx (*Lynx lynx*)[6]	C	30128	3800	7.93
polecat (*Mustela putorius*)[7]	C	9899	1097	9.02
wolverine (*Gulo gulo*)[8]	C	271109	1400	193.6
lemming (*Dicrostonyx groenlandicus*)[9]	H	212.9	15	14.08
mule deer (*Odocoileus hemionus*)[10]	H	11823	311	38.02
moose (*Alces alces*)[11]	H	24400	220	111.9
cotton rat (*Sigmodon hispidus*)[12]	H	4670	21	221.6
wild boar (*Sus scrofa*)[13]	O	274485	13280	20.67

[1]trophic level, [2]median dispersal distance, [3]daily movement distance, [4]Covell et al. 1996, [5]Zalewski et al. 2004, [6]Moa et al. 2001, [7]Brzezinski et al. 1992, [8]Renzhu et al. 1995, [9]Schmidt et al. 2002, [10] Krausman, unpub. data, [11]Courtois et al. 1998, [12]Sulok et al. 2004, [13]Spitz and Janeau 1990

Interpretations, Appraisals, and Applications

Spacing Wildlife Crossings: The Options

There are at least three potential options in spacing wildlife crossings using allometric distance domains. All involve scaling to home range area and are: a) the median dispersal distance (7 * √ Home Range), b) a linear dimension of home range (√ Home Range), c) and a scaling measure related to daily dispersal distance. Using the linear dimension of the species home range to develop scale domains is most conservative and places crossings closest together. The implication is that crossings are no further apart than the linear dimension of the largest home range in the scale domain. Using √ Home Range to establish scaling domains to inform the placement of wildlife crossings seems most reasonable because shorter dispersal distances by juveniles appear to be more frequent.[226] Additionally, animal fidelity to home range areas suggests that shorter individual movement distances predominate among all sexes and ages. Thus, the

linear scale approach would appear to promote greatest permeability (Figure 34, Table 38). A less conservative approach uses the median dispersal distance[33], i.e., seven times the linear dimension of home range, as the criteria for developing the scale domains. Longer distance dispersal does occur less frequently but is important for recolonizing areas as well as gene flow.[226] An intermediate approach might use daily movement distances to develop distance domains. Typically, one might expect that mammals would
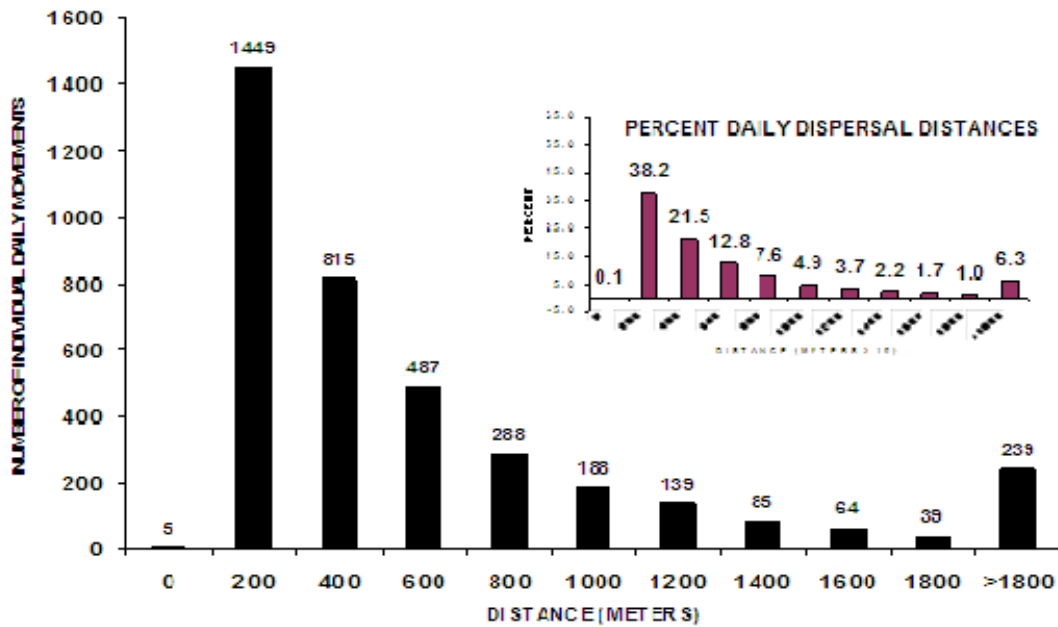
Figure 33: Distribution of daily movement distances of 46 telemetered mule deer from 1999-2003. Each individual movement represents the straight line distance between two relocations taken approximately 24 hours apart
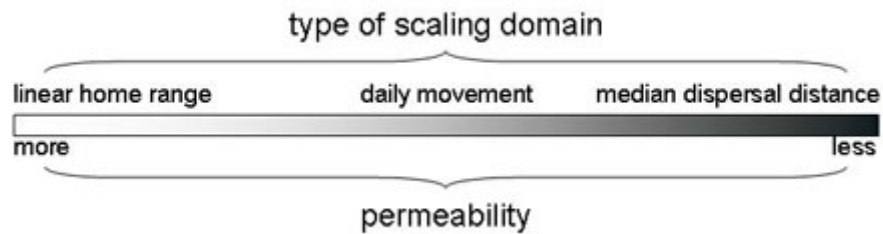
Figure 34: Degree of landscape permeability for mammalian species is dependent upon which distance domain (linear home range distance, daily movement or median dispersal distance) is used to develop the scaling domains, and hence the spacing between wildlife crossings

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travel significantly longer distances in their search for resources. To the extent that daily movement data are available for species, allometric domains can be developed to inform the placement of wildlife crossings. The sample given in Table 37 above, however, suggests that a large sample will be needed to extract the relationship, if it exists.

Conclusions

Placing Crossing Structures for Large Animals

Large terrestrial mammals, when involved in wildlife-vehicle crashes, tend to result in greater vehicle damage and greater potential for human injury and death than smaller body-sized animals. Large-bodied animals are a greater safety risk on the road. It appears that to achieve the kind of landscape permeability that will help insure the health of large mammal populations (i.e., deer, moose, elk, and bear) and to minimize wildlife-vehicle crashes, placement of wildlife crossings in areas where populations of these animals exist will entail at least a multi-step decision process. The first involves deciding which allometric scaling domain is appropriate and feasible. Highest permeability will be obtained when crossings of appropriate type and design are placed using the linear home range distance (Table 38). Crossings placed according to the median dispersal distance domains are clearly too far apart to create high permeability of the landscape. For example, placing wildlife crossings using the LHRD domain for white-tailed deer and mule deer at about 1 mile (1.6 km) apart in areas where these animals cross the road frequently and are often hit by vehicles, would certainly improve highway safety and help insure ease of movement, improving landscape permeability for these animals. Using the MedDD values of 6.1 to 7.4 miles to space the crossings for these deer species clearly is inappropriate and will do little to reduce A-V-Cs or facilitate movement. Similar arguments are appropriate for the other species listed in Table 38 and for all species in general. However, using scaling domains represents only the first step in insuring landscape permeability and improving highway safety. Local information about migration pathways, areas of local animal movement across roads, hotspots of animal vehicle crashes, and carcass data on the road provides essential additional information to inform the location of wildlife crossings.

Table 38: Home range of large mammals and derived scaling domains for wildlife crossing placement

SPECIES	HR (mi^2)	√ HR (mi)	Med DD (mi)
white-tailed deer (*Odocoileus virginianus*)	0.8	0.9	6.1
mule deer (*Odocoileus hemionus hemionus*)	1.1	1.1	7.4
pronghorn antelope (*Antilocapra americana*)	4.1	2.0	14.2
moose (*Alces alces*)	5.0	2.2	15.2
elk (*Cervus Canadensis*)	5.0	2.2	15.6
bighorn sheep (*Ovis Canadensis*)	5.5	2.4	16.5
black bear (*Ursus americanus*)	9.3	3.1	21.4
grizzly bear (*Ursus arctos*)	35.8	6.0	41.9

Caveats

Clustering techniques, such as the one used in this research, make no consideration for topography, land form, or landscape structure. They simply group similar clusters of animals based on specified criteria. When the clusters are used to group species by allometric distances, one implicit assumption is that all species use all parts of the landscape in a homogeneous manner. This clearly is not the case. Additionally, all measurements are derived ultimately from the published home range areas. The home range of an animal is an area traversed by the individual in its normal activities of food gathering, mating, and caring for young.[161] Home range area is a measure that implicitly assumes that the animal uses all parts of its range. Although there are some home range measurement techniques [i.e., the Center of Activity (e.g., Kernal Method, Worton[248])and the Nonparametric Method (e.g., area determination by GPS cartesian coordinates and analyzed with map software)] that measure not only the extent of the area used by the animal but also concentrations of activity within the home range, the oldest and most commonly used method is the minimum convex polygon home range estimator.[175] It estimates only area of use. A clearer and more concise measure of resource use can be obtained by following an animal's movement trajectory, and assessing what resources it is using, but this is seldom done and large data sets are unavailable. An advantage of following animal trajectories is that daily movement distances could be estimated. In summary, using home range area to establish allometric distance domains can be problematic; however, other consistently collected and reliable data are not widely available. A clear need is the gathering of a sufficient sample of accurate home range information. The use of the linear home range dimension, coupled with local knowledge of animal movements across the road, and with animal crash and carcass data provides an ecologically sound approach to inform the placement of animal crossing structures.

Acknowledgements

CHAPTER 4: DECISION TOOL UPDATE

The final product for this research is a decision tool to assist in the development of mitigation measures to reduce wildlife mortality in transportation corridors. The decision tool will initially be placed on the internet on our website www.widlifeandroads.org. At this stage, the basic outline of the website's decision tool has been developed with 7 steps listed in a hierarchical order. The user can follow these steps in the order presented, or jump to any step to answer a specific question. The hotlink for each step is found within each box of each step (Figure 35).

Consideration   **Do we need to consider mitigation measures?**
Selection   **What type of structures for what species and processes?**
Placement   **Where along the highway and on the landscape do we place these measures?**
Configuration   **What are the dimensions, materials, bottom surface, light and noise considerations, and human activities?**
Monitoring/Evaluation   **How do we assess the effectiveness of our efforts?**
Maintenance   **What actions are necessary to maintain structure efficacy?**
Final Plan   **Full suite of mitigation efforts and necessary actions, and how to enact them**

Figure 35: Decision tool steps

We have expanded the first step, _Consideration_, as an example of how a user can learn the answers to questions they may have. Every step will be similarly constructed. When the box _Consideration_ is clicked, a page with a series of topic boxes appears. The topic box current statements will be changed into the format of specific questions that the user may be interested in gaining assistance in answering and will find help in answering within the site (Figure 36).

Consideration
Do we need to consider mitigation measures?

Ecological Considerations

1. Determine natural areas of nearby & all species potentially affected by project, from ungulates to insects

2. Conversations with local-regional biologists

3. Consult Ecological Resources such as state wildlife action plans, connectivity analyses, which indicate if the area is known as important to sensitive species, wetlands, for connectivity, etc.

4. Local data collection on species presence is necessary, either past studies or new research

5. Regulatory requirements for wetlands (404 permits), endangered & threatened species presence, etc

Safety Considerations

Analyze animal-vehicle collision and carcass data to determine past problems with wildlife &vehicles in the area

Look for potential for wildlife-vehicle collisions by analyzing wildlife presence and movement corridors in the area, usually available from state wildlife agency

AASHTO recommendations. . .

Figure 36: Consideration topics found on the website

Each box, as well as an accompanying box hotlinked to related articles, will be hyperlinked to specific series of questions, references, lists, pictures, and website links.

The step by step process has multiple points where the user can access a website page or related links to find answers to their questions. There will also be a query function on the site, independent of the decision tool. We believe this query function will be very highly used by short term users of the site. The query button will use key words that the users enter to find multiple links of related articles, pictures, databases, and websites. For instance, all the pictures on the website will have linked key words so that a query asking about specific species, places, or crossing types will link the user with pictures that match the query. For example, a picture of a wildlife crossing for ungulates, which is along a stream and currently under construction in Montana, will be linked with the query functions by any of the key words: ungulate, deer, elk, moose, Montana, construction, riparian. Each step of the decision tool will have similar query functions.

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The following classes of data will all be linked to the query functions in the decision tool and on the query webpage (Figure 37).

Access Databases of Telephone Survey Results: crossings, driver warning systems, target species, states, dimensions, Ecoregions, etc.

Pictures, Diagrams

Websites

Query Function

Map of states and provinces, which also link to all the other related databases and sites (Interactive Map)

Literature Database with annotated listings (300+)

Articles: links and pdf files
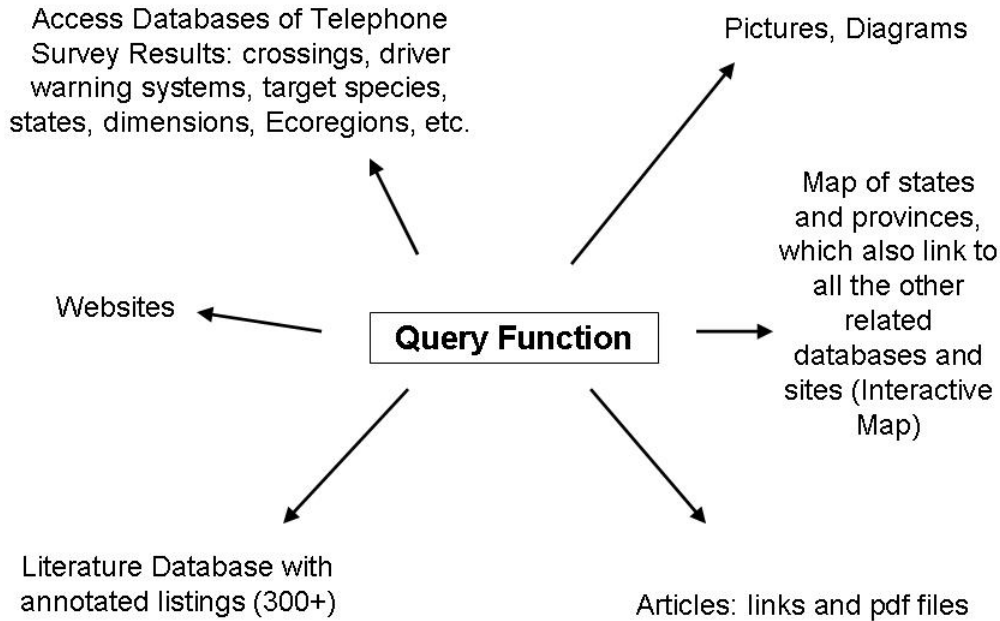
Figure 37: Query function and links within website and databases of this project

We realize that this site can become complicated and may confuse or overwhelm the user. We will organize the site in a way so that the user is able to see where they are as they navigate through the decision tool. This is done by tabs on the top of the page to show all seven steps and that indicate where the user is by the highlighted tab. This is similar to how airlines organize their sites for on-line booking of tickets. This "secondary breadcrumb trail," as it is called in the web development industry, will help users navigate back and forth within the site. We will also alert users when they have left the site to visit another linked site.

A unique property of this site will be the 'shopping cart.' This will allow the user to transfer files and website addresses into a final cart of products they can download. This feature allows the users to give an article or webpage just a cursory glance but save it in their final list of products to view and/or download later once they have used the decision tool.

Another aspect of the overall website is the ability of users to submit case histories and data. This information will be reviewed by the supervisor of the website and possibly a committee of professionals who can verify the accuracy of the new material. This leads to a dynamic website that is continually being updated in an ever changing

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world. Our intention is to make this the website of choice for all queries involved in wildlife and roads in North America. We will need to secure funding for future input and maintenance of this site, to keep it running and updated for the next decade or longer.

For a better comprehension of the decision tool, and the site overall, we recommend the reader visit the website: www.widlifeandroads.org. As an exercise in using the decision tool, we have suggested a series of steps a first time user may want to step through in order to get an understanding of how this process will proceed.

- If you visit our site at: www.wildlifeandroads.org, you can peruse through the site to see the different topics of information we will be presenting
- As you view the seven steps for the decision tool, you may move the cursor across the page, and see that it turns to a hand when it is held over any one of the seven step boxes, indicating each box is a link to further steps. For this example, please click on 'Consideration'
- The next page that comes up represents the different areas of information this step will consider. If you click on the yellow box on the lower right corner, you will be taken to the next page
- This page has two references and small examples of their abstracts available. If you are interested in seeing the full article, you may click on either reference and will automatically have that article appear. The Bissonette article is found in an on-line journal and the user is taken to that specific site. The Forman article is stored on our computers
- These articles result in the end of a search. Other pages in the decision tool will always have a button for getting the user back to the decision tool home, or previous page

LITERATURE CITED

1. Adams, L.W., "Small Mammal Use of an Interstate Highway Median Strip." *Journal of Applied Ecology*, Vol. 21 (1984) pp.175-178.

2. Adams, L.W. and Geis, A.D., "Effects of Roads on Small Mammals." *Journal of Applied Ecology*, Vol. 20 (1983) pp.403-415.

3. Addicott, J.F., Aho, J.M., Antolin, M.F., Padilla, D.K., Richardson, J.S. and Soluk, D.A., "Ecological Neighborhoods: Scaling Environmental Patterns." *Oikos*, Vol. 49 (1987) pp. 340-346.

4. Allen, R.E. and McCullough, D.R., "Deer-Car Accidents in Southern Michigan." *Journal of Wildlife Management*, Vol. 40 (1976) pp.317-325.

5. Anderson, D.R., Burnaham, K.P., White, G.C. and Otis, D.L., "Density Estimation of Small-Mammal Population Using a Trapping Web and Distance Sampling Methods." *Ecology*, Vol. 64 (1983) pp.674-680.

6. Anonymous, "Comprehensive Wildlife Conservation Strategies." *State Progress Report #2*, International Association of Fish and Wildlife Agencies, Washington, DC (2004). [http://www.teamingwithwildlife.org/]

7. Arcese, P., "Intrasexual Competition, Mating System, and Natal Dispersal in Song Sparrows." *Animal Behaviour*, Vol. 38 (1989) pp.958-979.

8. Ashley, M. and Wills, C., "Analysis of Mitochondrial DNA Polymorphisms Among Channel Island Deer Mice." *Evolution*, Vol. 41(1987) pp.854-863.

9. Austin, J., Viani, K. and Hammond, F., "Vermont Wildlife Habitat Linkage Analysis." *Report to Vermont Agency of Transportation*, VTrans Research Advisory Council No. RSCH008-967 (2006).

10. Baker, R.H., "Are Man-Made Barriers Influencing Mammalian Speciations?" *Journal of Mammalogy*, Vol. 79 (1998) pp.370-371.

11. Bank, F., Irwin, L., Evink, G., Gray, M., Hagood, S., Kinar, J., Levey, A., Paulson, D., Ruediger, B., Sauvajot R., Scott, D., White, P., "Wildlife Habitat Connectivity Across European Highways." *FHWA Report PL-02-011*, U.S. Department of Transportation, Federal Highway Administration, International Technology Exchange Program (2002).

12. Barnett, J.L., How, R.A. and Humphreys, W.F., "The Use of Habitat Components by Small Mammals in Eastern Australia." *Australian Journal of Ecology*, Vol. 3 (1978) pp.277-85.

13. Barnum, S., "Preliminary Analysis of Locations Where Wildlife Crosses Highways in the Southern Rocky Mountians." International Conference on Ecology and Transportation, Keystone, CO, Proceedings (2001) pp.565-573.

14. Barnum, S., "Identifying the Best Locations Along Highways to Provide Safe Crossing Opportunities for Wildlife." *CDOT Report CDOT-DTD-UCD-2003-9*, Colorado Department of Transportation, Research Branch, Denver, CO (2003).

15. Bashore, T.L., Tzilkowski, W.M. and Bellis, E.D., "Analysis of Deer-Vehicle Collision Sites in Pennsylvania." *Journal of Wildlife Management*, Vol. 49 (1985) pp.769-774.

16. Bates, K., "Design of Road Culverts for Fish Passage." *Washington Department of Fish and Wildlife Report*, Olympia, WA (2003).

17. Begon, M., Towsend, C.R. and Harper, J.L., Ecology – From Individuals to Ecosystems. Blackwell Publishing (2006) 738 pp.

18. Beier, P. and Barrett, R.H., "The Cougar in the Santa Ana Mountain Range, California." *Orange County Cooperative Final Report* (1993).

19. Bellamy, P.E., Shore, R.F., Ardeshir, D., Treweek, J. R. and Sparks, T. H., "Road Verges as Habitat for Small Mammals in Britain." *Mammal Review*, Vol. 30 (2000) pp.131-139.

20. Bellis, E.D. and Graves, H.B., "Deer Mortality on a Pennsylvania Interstate Highway." *Journal of Wildlife Management*, Vol. 35 (1971) pp.232-237.

21. Benfield, F.K., Raimi, M. and Chen, D.D.T., Once There Were Greenfields. Natural Resources Defense Council, NY (1999).

22. Bennetts, R.E., Nichols, J.D., Lebreton, J.D., Pradel, R., Hines, J.E. and Kitchens, W.M., "Methods for Estimating Dispersal Probabilities and Related Parameters Using Marked Animals." *Dispersal*, Oxford University Press, NY (2001) pp.3-17.

23. Beringer, J.J., Seibert, S.G. and Pelton, M.R., "Incidence of Road Crossing by Black Bears on Pisgah National Forest, North Carolina." International Conference on Bear Research and Management, Proceedings Vol.8 (1990) pp.85-92.

24. Beyer, H.L., Hawth's Analysis Tools for ArcGIS. (2004) http://www.spatialecology.com/htools.

25. Biggs, J., Sherwood, S., Michalak, S., Hansen, L., and Bare, C., "Animal-Related Vehicle Accidents at the Los Alamos National Laboratory, New Mexico." *The Southwestern Naturalist*, Vol. 49 (2004) pp.384-394.

26. Bissonette, J.A., "Scaling Roads and Wildlife: The Cinderella Principle." *Zeitschrift für Jagdwissenschaft (supplement)*, Vol. 48 (2002) pp.208-214.

27.   Bissonette, J. A., "Linking Landscape Patterns to Biological Reality." *Landscape Theory and Resource Management: Linking Theory to Practice*, Island Press, Covelo, CA (2003) pp.15-34.

28.   Bissonette, J. A. and Hammer, M., "Effectiveness of Earthen Return Ramps in Reducing Big Game Highway Mortality in Utah." *Report UT-01.09*, Utah Department of Transportation, Salt Lake City, UT (2000).

29.   Bissonette, J.A. and Storch, I., "Fragmentation: Is the Message Clear?" *Conservation Ecology*, Vol. 6 (2002) p.14. [online] http://www.consecol.org/vol6/iss2/art14

30.   Bissonette, J.A. and Storch, I., Landscape Theory and Resource Management: Linking Theory to Management. Island Press, Washington, DC (2003).

31.   Boarman, W.I., Sazaki, M. and Jennings, W.B., "The Effect of Roads, Barrier Fences, and Culverts on Desert Tortoise Populations in California, USA." Conservation, Restoration, and Management of Tortoises and Turtles- An International Conference, The New York Turtle and Tortoise Society, Proceedings (1997) pp.54-58.

32.   Boots, B.N. and Getis, A., Point Pattern Analysis. Sage Publications, Beverly Hills, CA (1988).

33.   Bowman, J., Jaeger, J.A.G., Fahrig, L., "Dispersal Distance of Mammals is Proportional to Home Range Size." *Ecology*, Vol. 83 (2002) pp.2049-2055.

34.   Bowne, D. R., and M. A. Bowers. 2004. Interpatch movements in spatially structured populations: A literature review. Landscape Ecology 19:1-20.

35.   Braumandl, T.F., Curran, M.P., Davis, G.D., Quesnel, H.J., Woods, G.P., DeLong, D.L. and Ketcheson, M.V., "Biogeoclimatic Subzones and Variants of the Nelson Forest Region." *A Field Guide for Site Identification and Interpretation for the Nelson Forest Region*, Land Management Handbook 20, Ministry of Forests, Victoria, BC Canada (1992) pp. 44-199.

36.   Brock, R.E. and Kelt, D.A., "Influence of Roads on the Endangered Stephens' Kangaroo Rat (*Dipodomys stephensi*): Are Dirt and Gravel Roads Different?" *Biological Conservation*, Vol. 118 (2004) pp.633-640.

37.   Brown, J.H., Macroecology. University of Chicago Press, Chicago, IL (1995).

38.   Bullock, J.M., Kenward, R.E., Hails, R., Dispersal Ecology. Blackwell Science, Oxford, England (2002).

39.   Brzezinski, M., Jedrzejewski, W. and Jedrzejewska, B., "Winter Home Ranges and Movement of Polecats *Mustela putorius* in Bialowieza Primeval Forest, Poland." *Acta Theriologica*, Vol. 37 (1992) pp.181-191.

40. Buckland, S.T., Anderson, D.R., Burnham, K.P. and Laake, J.L., Distance Sampling: Estimating Abundance of Biological Populations. Chapman and Hall, London, England (1993).

41. Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. and Thomas, L., Introduction to Distance Sampling. Oxford University Press, London, England (2001).

42. Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. and Thomas, L., Advanced Distance Sampling. Oxford University Press (2004).

43. Burnett, S.E., "Effects of a Rainforest Road on Movements of Small Mammals: Mechanisms and Implications." *Wildlife Research*, Vol.19 (1992) pp.5-104.

44. Burt, W.H., "Territoriality and Home Range Concepts as Applied to Mammals." *Journal of Mammalogy*, Vol. 24 (1943) pp.346-352.

45. Carbaugh, B., Vaughan, J.P., Bellis, E.D. and Graves, H.B., "Distribution and Activity of White-tailed Deer Along an Interstate Highway." *Journal of Wildlife Management*, Vol. 39 (1975) pp.570-581.

46. Carr, M., Hoctor, T., Goodison, C., Zwick, P., Green, J., Hernandez, P., McCain, C., Teisinger, J., Whitney, K., "Southeastern Ecological Framework." *Final Report*, Geoplan Center, Departments of Landscape Architecture, Urban and Regional Planning, and Wildlife Ecology and Conservation, University of Florida, Gainesville, FL (2002).

47. Case, R.M., "Interstate Highway Road-killed Animals: A Data Source for Biologists." *Wildlife Society Bulletin*, Vol. 6 (1978) pp.8-13.

48. Cherry, S., "A Comparison of Confidence Interval Methods for Habitat Use-Availability Studies." *Journal of Wildlife Management*, Vol. 60 (1996) pp.653-658.

49. Clark, B.K., Clark, B.S., Johnson, L.A. and Hayne, M.T., "Influence of Roads on Movements of Small Mammals." *Southwestern Naturalist*, Vol. 46 (2001) pp.338-344.

50. Clark, P.J. and Evans, F.C., "Distance to Nearest Neighbor as a Measure of Spatial Relationships in Populations." *Ecology*, Vol. 35 (1954) pp.445-453.

51. Clevenger, A.P., Chruszcz, B., and Gunson, K.E., "Highway Mitigation Fencing Reduces Wildlife-Vehicle Collisions." *Wildlife Society Bulletin*, Vol. 29 (2001) pp.646-653.

52. Clevenger, A.P., Chruszcz, B., and Gunson, K.E., "Spatial Patterns and Factors Influencing Small Vertebrate Fauna Road-kill Aggregations." *Biological Conservation*, Vol. 109 (2003) pp.15-26.

53.	Clevenger, A.P., Chruszcz, B., Gunson, K. and Wierzchowski, J., "Roads and Wildlife in the Canadian Rocky Mountain Parks - Movements, Mortality and Mitigation." *Final Report*, Parks Canada, Banff, Alta, Canada (2002).

54.	Clevenger, A.P., Purroy, F.J. and Campos, M.A., "Habitat Assessment of a Relict Brown Bear *Ursus arctos* Population in Northern Spain." *Biological Conservation*, Vol. 80 (1997) pp.17-22.

55.	Clevenger, A.P. and Waltho, N., "Dry Drainage Culvert Use and Design Considerations for Small- and Medium-sized Mammal Movement Across a Major Transportation Corridor." International Conference on Wildlife Ecology and Transportation, Proceedings (1999) pp.263-277.

56.	Clevenger, A.P. and Waltho, N., "Factors Influencing the Effectiveness of Wildlife Underpasses in Banff National Park, Alberta, Canada." *Conservation Biology*, Vol. 14 (2000) pp.47-56.

57.	Clevenger, A.P. and Waltho, N., "Long-term Year-round Monitoring of Wildlife Crossing Structures and the Importance of Temporal and Spatial Variability in Performance Studies." International Conference on Ecology and Transportation, Lake Placid, NY, Proceedings (2003) pp.293-302.

58.	Clevenger, A.P. and Waltho, N., "Performance Indices to Identify Attributes of Highway Crossing Structures Facilitating Movements of Large Mammals." *Biological Conservation*, Vol. 121 (2005) pp.453-464.

59.	Clobert, J., Wolff, J.O., Nichols, J.D., Danchin, E. and Dhondt, A.A., "Introduction." *Dispersal*, Oxford University Press, NY (2001) pp xvii-xxi.

60.	Connelly, J.W., Knick, S.T., Schroeder, M.A. and Stiver, S.J., "Conservation Assessment of Greater Sage-Grouse and Sagebrush Habitats." *Unpublished report*, Western Association of Fish and Wildlife Agencies, Cheyenne, WY (2004).

61.	Conover, M.R., Pitt, W.C., Kessler, K.K., DuBow, T.J. and Sanborn, W.A., "Review of Human Injuries, Illnesses, and Economic Losses Caused by Wildlife in the United States." *Wildlife Society Bulletin*, Vol. 23 (1995) pp.407-414.

62.	COST 341. 2006. Url: http://cordis.europa.eu/cost-transport/src/cost-341.htm.

63.	Courtois, R., Labonte, J. and Ouelle, J.P., "Déplacements et Superficie du Domaine Vital de l'Orignal, *Alces alces*, dans l'Est du Quebec." *Canadian-Field Naturalist*, Vol. 112 (1998) pp.602-610.

64.	Covell, D.F., Miller, D.S. and Darasov, W.H., "Cost of Locomotion and Daily Energy Expenditure by Free-living Swift Foxes (*Vulpes velox*): A Seasonal Comparison." *Canadian Journal of Zoology*, Vol. 74 (1996) pp.283-290.

65. Craighead, A.C., Craighead, F.L. and Roberts, E.A., "Bozeman Pass Wildlife Linkage and Highway Safety Guide." International Conference on Ecology and Transportation, Keystone, CO, Proceedings (2001) pp 405-412.

66. Cramer, P.C. and Bissonette, J.A., "Wildlife Crossings in North America: The State of the Science and Practice." International Conference on Ecology and Transportation, San Diego, CA, Proceedings (2006) pp.442-447.

67. Cressie, N., Statistics for Spatial Data. John Wiley and Sons, NY (1991).

68. Damuth, J., "Population Density and Body Size in Mammals." *Nature*, Vol. 290 (1981) pp.699-700.

69. Davidson, D., "Innovative Partnerships that Address Highway Impacts to Wildlife Habitat Connectivity in the Northern Rockies. International Conference on Ecology and Transportation, Lake Placid, NY, Proceedings (2003) pp.195-203.

70. Dillman, D.A., Mail and Internet Surveys: The Tailored Design Method. John Wiley and Sons, Inc., NY (2000).

71. Dodd, C.K., Barichivich, W.J. and Smith, L.L., "Effectiveness of a Barrier Wall and Culverts in Reducing Wildlife Mortality on a Heavily Traveled Highway in Florida." *Biological Conservation*, Vol. 118 (2004) pp.619-631.

72. Dodd, N. L., "Characteristics of Elk-Vehicle Collisions and Comparison to GPS-Deterimined Highway Crossing Patterns." International Conference on Ecology and Transportation, San Diego, CA, Proceedings (2006) pp. 461-477.

73. Dodd, N.L., Gagnon, J. and Schweinsburg, R., "Evaluation of Measures to Minimize Wildlife-Vehicle Collisions and Maintain Wildlife Permeability Across Highways." *Quarterly Progress Report 10*, Submitted to the Research Techinical Advisory Committee and Project Implementation Working Group, Arizona Game and Fish Department, Research Branch, Phoenix, AZ (2004).

74. Dodd, N.L., Gagnon, J.W. and Schweinsburg, R.E., "Phases II and III: Evaluation of Measures to Minimize Wildlife-Vehicle Collisions and Maintain Wildlife Permeability Across Highways." *Progress Report*, Arizona Game and Fish Department (2006).

75. Doerr, E.D., Doerr, V.A.J., "Dispersal Range Analysis: Quantifying Individual Variation in Dispersal Behaviour." *Oecologia*, Vol. 142 (2005) pp.1-10.

76. Endries, M., Gilbert, T. and Kautz, R., "Environmental Planning in Florida: Mapping Wildlife Needs in Florida: The Integrated Wildlife Habitat Ranking System." International Conference on Ecology and Transportation, Lake Placid, NY, Proceedings (2003) pp.525-533.

77. Environmental Systems Research Institute, ArcView GIS Version 3.3., Redlands, CA (1999).

78. Environmental Systems Research Institute, ArcGIS version 9.0, Redlands, CA (2003).

79. Evink, G., "NCHRP Synthesis 305: Interaction Between Roadways and Wildlife Ecology: a Synthesis of Highway Practice." *National Cooperative Highway Research Program Report*, Washington, DC (2002).

80. Evink, G., "Wetlands, Wildlife, and Ecosystems." Environmental Research Needs in Transportation Conference, Transportation Research Board, Washington DC (2002).

81. Fahrig, L., Pedlar, J.H., Pope, S.E., Taylor, P.D. and Wegner, J.F., "Effect of Road Traffic on Amphibian Density." *Biological Conservation*, Vol. 74 (1995) pp.177-182.

82. Farrell, J.E., Irby, L.R., McGowen, P.T., "Strategies for Ungulate Vehicle Collision Mitigation." *Intermountain Journal of Science*, Vol. 8 (2002) pp.1-18.

83. Federal Highway Administration, "America's Highways 1776-1976: A History of the Federal Aid Program." *US Department of Transportation Report*, Washington DC (1979).

84. Federal Highway Administration, "Highway Statistics 2002: Roadway Extent, Characteristics and Performance." *US Department of Transportation Report*, Washington DC (2002).

85. Federal Highway Administration, "Keeping it Simple: Easy Ways to Help Wildlife Along Roads." *US Department of Transportation Report*, Washington, DC (2006).

86. Feldhammer, G.A., Gates, J.E., Harman, D.M., Loranger, A.J. and Dixon, K.R., "Effects of Interstate Highway Fencing on White-tailed Deer Activity." *Journal of Wildlife Management*, Vol. 50 (1986) pp.497-503.

87. Ferreras, P., Aldama, J.J., Beltran, J.F. and Delibers, M., "Rates and Causes of Mortality in a Fragmented Population of Iberian Lynx *Felis pardini* Temminck, 1824." *Biological Conservation*, Vol. 61 (1992) pp.197-202.

88. Finder, R.A., "Relationships between Landscape Patterns and White-tailed Deer/Vehicle Accidents." Master's Thesis, Southern Illinois University-Carbondale, IL (1997).

89. Finder, R.A., Roseberry, J.L. and Woolf, A., "Site and Landscape Conditions at White-tailed Deer-Vehicle Collision Locations in Illinois." *Landscape and Urban Planning*, Vol. 44 (1999) pp.77-85.

90. Findlay, C.S. and Houlahan, J., "Anthropogenic Correlates of Species Richness in Southeastern Ontario Wetlands." *Conservation Biology*, Vol. 11 (1997) pp.1000-1009.

91. Fletcher, D.R., "Environmental Spatial Information for Transportation: A Peer Exchange on Partnerships." *TRB Workshop Woods Hole, MA Report*, Transportation Research Board, Washington, DC (2004).

92. Florida Fish and Wildlife Commission, "Integrated Wildlife Habitat Ranking System." GIS data, on compact disc, Florida Fish and Wildlife Commission, Tallahassee, FL (2004).

93. Foresman, K., "Monitoring Animal Use of Modified Drainage Culverts on the South Lolo Project." *Report FHWA/MT-01-004/8117-15*, Prepared for the State of Montana in cooperation with the U.S. Department of Transportation, Federal Highway Administration (2001).

94. Foresman, K., "Small Mammal Use of Modified Culverts on the Lolo South Project of Western Montana- an Update." International Conference on Ecology and Transportation, Lake Placid, NY, Proceedings (2003) pp. 342-343.

95. Forman, R.T.T. and Alexander, L.E., "Roads and Their Major Ecological Effects." *Annual Review of Ecology and Systematics*, Vol. 29 (1998) pp.207-231.

96. Forman, R.T., Friedman, D.S., Fitzhenry, D., Martin, J.D., Chen, A.S. and Alexander, L.E., "Ecological Effects of Roads: Toward Three Summary Indices and an Overview for North America." *Habitat Fragmentation & Infrastructure*, Delft, Netherlands, Ministry of Transport, Public Works and Water Management (1997) pp.40-54.

97. Forman, R.T., Reineking, B., and Hersperger, A.M., "Road Traffic and Nearby Grassland Bird Patterns in a Suburbanizing Landscape." *Environmental Management*, Vol. 29 (2002) pp.782-800.

98. Forman, R.T., Sperling, D., Bissonette, J.A., Clevenger, A.P., Cutshall, C.D., Dale, V.H., Fahrig, L., France, R., Goldman, C.R., Heanue, K., Jones, J.A., Swanson, F.J., Turrentine, T. and Winter, T.C., Road Ecology: Science and Solutions. Island Press, Washington, DC (2003).

99. Foster, M. and Humphrey, S., "Effectiveness of Wildlife Crossings in Reducing Animal Auto Collisions on Interstate 75, Big Cypress Swamp, Florida." *Florida Department of Transportation and University of Florida Report*, Gainesville, FL (1992).

100. Foster, M. and Humphrey, S., "Use of Highway Underpasses by Florida Panthers and Other Wildlife." *Wildlife Society Bulletin*, Vol. 23 (1995) pp.95-100.

101. Fuller,T., "Population Dynamics of Wolves in North-central Minnesota." *Wildlife Monographs*, Vol. 105 (1989) pp.1-41.

102. Gagnon, J., Dodd, N.L. and Manzo, A.L., "Use of Video Surveillance to Assess Wildlife Behavior and Use of Wildlife Underpasses in Arizona." International Conference on Ecology and Transportation, San Diego, CA, Proceedings (2006) pp. 534-544.

103. Gerlach, G. and Musolf, K., "Fragmentation of Landscapes as a Cause for Genetic Subdivision in Bank Voles." *Conservation Biology*, Vol. 14 (2000) pp.1066-1074.

104. Getis, A. and Franklin, J., "Second-Order Neighborhood Analysis of Mapped Point Patterns." *Ecology*, Vol. 68 (1987) pp.473-477.

105. Gibeau, M.L., "A Conservation Biology Approach to Management of Grizzly Bears in Banff National Park, Alberta." Ph.D. thesis, University of Calgary, Calgary, AB Canada (2000) 129 pp.

106. Gibeau, M.L. and Herrero, S., "Roads, Rails and Grizzly Bears in the Bow River Valley, Alberta." International Conference on Wildlife Ecology and Transportation, Fort Meyers, FL, Proceedings (1998) pp.104-108.

107. Goosem, M., "Effects of Tropical Rainforest Roads on Small Mammals: Inhibition of Crossing Movements." *Wildlife Research*, Vol. 28 (2001) pp.351-364.

108. Griffith, M.S. and Council, F.M., "The Highway Safety Information System: United States Department of Transportation Multi-State Safety Analysis Database." Traffic Safety on Two Continents Conference, Malmo, Sweden, Proceedings (2000).

109. Gunther, K., Biel, M.J. and Robison, H.L., "Influence of Vehicle Speed and Vegetation Cover Type on Road-killed Wildlife in Yellowstone National Park." Wildlife and highways: seeking solutions to an ecological and socio-economic dilemma, The Seventh Annual Meeting of The Wildlife Society, Nashville, Tennessee, Proceedings (2000).

110. Hansen, A.J., Rasker, R., Maxwell, B., Rotella, J.J., Johnson, J.D., Parmenter, A.W., Langner, U., Cohen, W.B., Lawrence, R.L. and Kraska, M.P.V., "Ecological Causes and Consequences of Demographic Change in the New West." *BioScience*, Vol. 52 (2002) pp.151-162.

111. Hardy, A., Clevenger, A.P., Huijser, M. and Neale, G., "An Overview of Methods and Approaches for Evaluating the Effectiveness of Wildlife Crossing Structures: Emphasizing the Science in Applied Science." International Conference on Ecology and Transportation, Lake Placid, NY, Proceedings (2003) pp. 319-330.

112. Harestad, A.S. and Bunnell, F.L., "Home Range and Body Weight—A Reevaluation." *Ecology*, Vol. 60 (1979) pp.389-402.

113. Harwood, D., Council F., Hauer, E., Hughes W. and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways". *FHWA Report FHWA-RD-99-207*, Federal Highway Administration, Washington, DC (2000).

114. Hauer, E., Observational Before-after Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety. Pergamon Press, Elsevier Science Ltd, Oxford, England (1997).

115. Hawbaker, T.J. and Radeloff, V.C., "Roads and Landscape Pattern in Northern Wisconsin Based on a Comparison of Four Road Data Sources." *Conservation Biology*, Vol. 18 (2004) pp.123-125.

116. Hedlund, J.H., Curtis, P.D., Curtis, G. and Williams, A.F., "Methods to Reduce Traffic Crashes Involving Deer: What Works and What Does Not." *Insurance Institute for Highway Safety Report*, Arlington, VA (2003).

117. Hengeveld, R., "Small Step Invasion Research." *Trends in Ecology and Evolution*, Vol. 9 (1994) pp.339-342.

118. Hewitt, D.G., Cain, A., Tuovila, V., Shindle, D.B. and Tewes, M.E., "Impacts of an Expanded Highway on Ocelots and Bobcats in Southern Texas and Their Preferences for Highway Crossings." International Conference on Ecology and Transportation, Ft. Meyers, FL, Proceedings (1998) pp. 126-134.

119. Heydecker, B.J. and Wu, J., "Using the Information in Road Crash Records." 19th Petroleum Technology Research Centre Summer Annual Meeting, London, England, Proceedings (1991).

120. Hjeljord, O., "Dispersal and Migration in Northern Forest Deer - Are There Unifying Concepts?" *Alces*, Vol. 37 (2001) pp.353-370.

121. Holland, W.D. and Coen, G.M., "Ecological Land Classification of Banff and Jasper National Parks." *The Wildlife Inventory Report Volume III*, Canadian Wildlife Service, Edmonton, AB Canada (1983).

122. Holling, C.S., "Cross-Scale Morphology, Geometry, and Dynamics of Ecosystems." *Ecological Monographs*, Vol. 62 (1992) pp.447-502.

123. Hosmer, D.W. and Lemeshow, S., Applied Logistic Regression. John Wiley and Sons, NY (1989).

124. Hubbard, M.W.,Danielson, B.J. and Schmitz, R.A., "Factors Influencing the Location of Deer-Vehicle Accidents in Iowa." *Journal of Wildlife Management*, Vol. 64 (2000) pp.707-713.

125. Huijser, M.P.,Gunson, K.E. and Abrams, C., "Wildlife-vehicle colllisions and Habitat Connectivity Along Montana Highway 83 in the Seeley-Swan Valley, Montana: A Reconnaissance." *Western Transportation Institute Report No. FHWA/MT-05-009/8177*, Montana State University, Bozeman, MT (2006).

126. Huijser, M.P.,Galarus, D.E. and Hardy, A., "Software for Pocket PC to Collect Road-Kill Data." International Conference on Ecology and Transportation, San Diego, CA, Proceedings (2006) p. 640.

127. International Conference on Ecology and Transportation: A Time for Action, Keystone, CO, Proceedings (2001).

128. International Conference on Ecology and Transportation: Making Connections, Lake Placid, NY, Proceedings (2003).

129. Iuell, B., Bekker, C.J., Cuperus, R., Dufek, J., Fry, G., Hicks, C., Hlavac, V., Keller, V., Rosell, C., Sangwine, T., Torslov, N. and Wandall, B., Wildlife and Traffic: A European Handbook for Identifying Conflicts and Designing Solutions. KNNV Publishers, Brussels, Belgium (2003)

130. Jackson, S.D., "Proposed Design and Considerations for Use of Amphibian and Reptile Tunnels in New England." *University of Massachusetts Report*, Amherst, MA (2003) URL: http/umass.edu/nrec/onlinedoces.html2003.

131. Jackson, S.D. and Tyning, T.F., "Effectiveness of Drift Fences and Tunnels for Moving Spotted Salamanders *Ambystoma maculatum* Under Roads." Amphibians and Roads, The Toad Tunnel Conference, ACO Polymer Products, Shefford, England, Proceedings (1989) pp.93-99.

132. Jaeger, J.A.G., "Landscape Division, Splitting Index, and Effective Mesh Size: New Measures of Landscape Fragmentation." *Landscape Ecology*, Vol. 15 (2000) pp.115-130.

133. Jaeger, J.A.G., Bowman, J., Brennan, J., Fahrig, L., Bert, D., Bouchard, J., Charbonneau, N., Frank, K., Gruber, B., Von Toschanowitz, K., "Predicting When Animal Populations Are at Risk From Roads: An Interactive Model of Road Avoidance Behavior." *Ecological Modeling*, Vol. 185 (2005) pp.329:348.

134. Joyce, T.L. and Mahoney, S.P., "Spatial and Temporal Distributions of Moose-Vehicle Collisions in Newfoundland." *Wildlife Society Bulletin*, Vol. 29 (2001) pp.281-291.

135. Kaseloo, P.A. and Tyson, K.O., "Synthesis of Noise Effects on Wildlife Populations." *Report Prepared for U.S. Department of Transportation*, Federal Highway Administration, McLean, VA. 2004.

136. Kassar, C. and Bissonette, J.A., "Deer-Vehicle Crash Hotspots in Utah: Data for Effective Mitigation." *UTCFWRU Project report No. 2005(1): 1-128*, Utah

Cooperative Fish and Wildlife Research Unit, Utah State University, Logan, UT (2005).

137. Kattan, G., Hernandez, O.L., Goldstein, I., Rojas, V., Murillo, O., Gomez, C., Restrepo, H. and Cuesta, F., "Range Fragmentation in the Spectacled Bear *Tremarctos ornatus* in the Northern Andes." *Oryx*, Vol. 38 (2004) pp.155-163.

138. Keller, I., Largiader, C.R. and Nentwig, W., "Recent Fragmentation Due to Major Roads Leads to a Reduction of Gene Flow in Ground Beetles." International Conference on Habitat Fragmentation due to Transportation Infrastructure, Brussels, Belgium, Proceedings (2003).

139. Kelt, D.A., Van Vuren, D.H., "The Ecology and Macroecology of Mammalian Home Range Area." *American Naturalist*, Vol. 157 (2001) pp.637-645.

140. Kintsch, J., "Linking Colorado's Landscapes." International Conference on Ecology and Transportation, San Diego, CA, Proceedings (2006) pp.138-142.

141. Kleiber, M. The Fire of Life: An Introduction to Animal Energetics. John Wiley and Sons, NY (1961).

142. Knapp, K. Pooled fund proposal (2004). url: http://www.pooledfund.org/documents/solicitations/906.pdf

143. Kozell, R.M. and Fleharty, E.D., "Movements of Rodents Across Roads." *Southwestern Naturalist*, Vol. 24 (1979) pp.239-248.

144. Lemel, J., Truve, J. and Soderberg, B., "Variation in Ranging and Activity Behaviour of European Wild Boar *Sus scrofa* in Sweden." *Wildlife Biology*, Vol 9, Supplement 1 (2003) pp.29-36.

145. Levine, N., Crimestat: A Spatial Statistics Program for the Analysis of Crime Incident Locations. Ned Levine and Associates, Annandale, VA and National Institute of Justice, Washington, DC (1999).

146. Levine, N., CrimeStat III: A Spatial Statistics Program for the Analysis of Crime Incident Locations. Ned Levine and Associates, Houston, TX and the National Institute of Justice, Washington, DC (2004).

147. Lindstedt, S.L, Miller, B.J. and Buskirk, S.W., "Home Range, Time, and Body Size in Mammals." *Ecology*, Vol. 67 (1986) pp.413-418.

148. Lloyd, J. and Casey, A., "Wildlife Hotspots Along Highways in Northwestern Oregon." *Report to Oregon Department of Transportation*, Portland, OR (2005).

149. Little, S.J., Harcourt, R.G. and Clevenger, A.P.,"Do Wildlife Passages Act as Prey Traps?" *Biological Conservation*, Vol. 107 (2002) pp.135-145.

150.   Lotz, M.A., Land, E.D. and Johnson, K.G., "Evaluation of State Road 29 Wildlife Crossings." *Final Report to the Florida Game and Fresh Water Fish Commission*, Tallhassee, FL (1996).

151.   Lyon, A.G. and Anderson, S.H., "Potential Gas Development Impacts on Sage Grouse Nest Initiation and Movement." *Wildlife Society Bulletin*, Vol. 31 (2003) pp.486-491.

152.   MacDonald, L.A. and Smith, S., "Bridge Replacements: An Opportunity to Improve Habitat Connectivity." International Conference on Wildlife Ecology and Transportation, Missoula, MT, Proceedings (1999).

153.   Mader, H.J., "Animal Habitat Isolation by Roads and Agricultural Fields." *Biological Conservation*, Vol. 29 (1984) pp.81-96.

154.   Mader, H.J., Schell, C. and Kornacker, P., "Linear Barriers to Arthropod Movements in the Landscape." *Biological Conservation*, Vol. 54 (1990) pp.209-222.

155.   Maehr, D.S., Land, E.D. and Roelke, M.E., "Mortality Patterns of Panthers in Southwest Florida." Annual Conference of the Southeastern Association Fish and Wildlife Agencies, Proceedings Vol. 45 (1991) pp.201-207.

156.   Maine Department of Transportation, "Collisions Between Wildlife Species and Motor Vehicles in Maine 1997-2001." *Traffic Engineering Division Report*, Bureau of Maintenance and Operations, Maine Department of Transportation, Augusta, ME (2002).

157.   Maine Department of Transportation, "Fish Passage Policy and Design Guide." *Maine Department of Transportation Report*, Environmental Office, Augusta, ME (2004). url: www.maine.gov/mdot/environmentalofficehomepage/pdf/policyanddesignguide2004.pdf.

158.   Malo, J.E., Suarez, F. and Diez, A., "Can We Mitigate Wildlife-vehicle Accidents Using Predictive Models*?" Journal of Applied Ecology*, Vol. 41 (2004) pp.701-710.

159.   Mansfield, T.M. and Miller, B.D., "Highway Deer-kill District 02 Regional Study." *Caltrans Internal Report*, Sacramento, CA (1975).

160.   McCaffrey, K.R., "Road-kills Show Trends in Wisconsin Deer Populations." *Journal of Wildlife Management*, Vol. 37 (1973) pp.212-216.

161.   McCune, B. and Grace, J. B., Analysis of Ecological Communities. MjM Software Design, ISBN 0-9721290-0-6, Gleneden Beach, OR (2002).

162. McCune, B. and Mefford, M.J., PC-ORD: Multivariate Analysis of Ecological Data. Version 4.36, MjM Software, Gleneden Beach, OR, (1999).

163. McGuire, T., "Connecting Values, Process, and Project Design: Twinning the Trans-Canada Highway in Banff National Park in Canada." International Conference on Ecology and Transportation, San Diego, CA, Proceedings (2006) p.77

164. McIninch, S.P. and Garman, G.C., "Strategies for Impediment Rehabilitation to Create Fish Passage Opportunities in the Rappahannock River Basin." *Report VTRC 04-CR2*, Submitted to theVirginia Transportation Research Council,Virginia Commonwealth University, VA (2004).

165. McNab, B.K., "Bioenergetics and the Determination of Home Range Size." *American Naturalist*, Vol. 97 (1963) pp.133-140.

166. Mech, L.D., Fritts, S.H., Raddle, G.L. and Paul, W.J., "Wolf Distribution and Road Density in Minnesota." *Wildlife Society Bulletin*, Vol. 16 (1988) pp.85-87.

167. Menard, S., "Applied Logistic Regression Analysis" *Sage University Paper Series Report 07-106*, Sage Publications, Thousand Oaks, CA (1995).

168. Merriam, G., "Important Concepts From Landscape Ecology for Game Biologists." *Gibier Faune Sauvage*, Vol 15 (1998) pp.525-531.

169. Meyer, E. and Ahmed, I., "Modeling of Deer-Vehicle Crash Likelihood Using Roadway and Roadside Characteristics." Transportation Research Board Annual Meeting, Proceedings (2004) CDROM.

170. Mills, S.L. and Conrey, R.Y., "Highways as Potential Barriers to Movement and Genetic Exchange in Small Mammals." *Final Report to Montana Department of Transportation*, University of Montana, School of Forestry, Missoula, MT (2003).

171. Mladenoff, D.J., Sickley, T.A., Haight, R.G. and Wydeven, A.P., "A Regional Landscape Analysis and Prediction of Favorable Gray Wolf Habitat in the Northern Great Lakes Region." *Conservation Biology*, Vol. 9 (1995) pp.279-94.

172. Mladenoff, D.J., Sickley, T.A. and Wydeven, A.P., "Predicting Gray Wolf Landscape Recolonization: Logistic Regression Models vs. New Field Data." *Ecological Applications*, Vol. 9 (1999) pp.37-44.

173. Moa, P., Negard, A., Overskaug, K. and Kvam, T., "Possible Effects of the Capture Event on Subsequent Space Use by Eurasian Lynx." *Wildlife Society Bulletin*, Vol. 29 (2001) pp.86-90.

174. Mohr, C.O., "Comparative Populations of Game, Fur, and Other Mammals." *American Midland Naturalist*, Vol. 24 (1940) pp.581-584.

175. Mohr, C.O., "Table of Equivalent Populations of North American Mammals." *American Midland Naturalist*, Vol. 37 (1947) pp.223-249.

176. Morrison, M.L., Marcot, B.G. and Mannan, R.W., Wildlife-Habitat Relationships. University of Wisconsin Press, Madison, WI (1992).

177. Mysterud, A., "Temporal Variation in the Number of Car-killed Red Deer *Cervus elaphus* in Norway." *Wildlife Biology*, Vol. 10 (2004) pp.203-211.

178. Nagorsen, D.W., "Rodents and Lagomorphs of British Columbia." *Mammals of British Columbia*, Volume 4, Royal British Columbia Museum, Victoria, BC Canada (2005).

179. Nathan, R., "Dispersal Biogeography." *Encyclopedia of Biodiversity*, Academic Press, San Diego CA (2001) pp.127-152.

180. Nathan, R., Perry, G., Cronin, J.T., Strand, A.E., Cain, M.L., "Methods for Estimating Long-Distance Dispersal." *Oikos*, Vol. 103 (2003) pp.261-273.

181. National Research Council, "Assessing and Managing the Ecological Impacts of Paved Roads." *Transportation Research Board Report*, National Research Council of the National Academies, Committee on Ecological Impact of Road Density, Board of Environmental Studies and Toxicology, Division of Earth and Life Studies, The National Academies Press, Washington, DC (2006).

182. Neigel, J.E. and Avise, J.C., "Application of a Random Walk to Geographic Distributions of Animal Mitochondrial DNA Variation." *Genetics*, Vol. 135 (1993) pp.1209-1220.

183. Nielsen, C.K., Anderson, R.G. and Grund, M.D., "Landscape Influences on Deer-Vehicle Accident Areas in an Urban Environment." *Journal of Wildlife Management*, Vol. 67 (2003) pp.46-51.

184. Noss, R.F., "Landscape Connectivity: Different Functions at Different Scales." *Landscape Linkages and Biodiversity*, Island Press,Washington, DC (1991) pp.27-39.

185. O'Driscoll, R.L., "Descriptions of Spatial Pattern in Seabird Distributions Along Line Transects Using Neighbour *K* Statistics." *Marine Ecology Progress Series*, Vol. 165 (1998) pp.81-94.

186. Oxley, D.J., Fenton, M.B. and Carmody, G.R., "The Effects of Roads on Populations of Small Mammals." *Journal of Applied Ecology*, Vol. 11(1974) pp.51-59.

187. Penrod, K., Hunter, R. and Merrifield, M., "Missing Linkages: Restoring Connectivity to the California Landscape." Conference Co-Sponsored by California Wilderness Coalition, The Nature Conservancy, U.S. Geological

Survey, Center for Reproduction of Endangered Species, and California State Parks, Proceedings (2001).

188. Poll, D.M., Porter, M.M., Holroyd, G.L., Wershler, R.M. and Gyug, L.W., "Ecological Land Classification of Kootenay National Park." *Wildlife Resource*, Volume II, Canadian Wildlife Service, Edmonton, AB Canada (1984).

189. Proctor, M.F., McLeleean, B.N. and Strobeck, C., "Population Fragmentation of Grizzly Bears in Southeastern British Columbia, Canada." *Ursus*, Vol. 13 (2002) pp.153-160.

190. Puglisi, M.J., Lindzey, J.S. and Bellis, E.D., "Factors Associated with Highway Mortality of White-tailed Deer." *Journal of Wildlife Management*, Vol. 38 (1974) pp.799-807.

191. Putman, R.J., "Deer and Road Traffic Accidents: Options For Management." *Journal of Environmental Management*, Vol. 51 (1997) pp.43-57.

192. Ramp, D., Caldwell, J., Edwards, K., Warton, D. and Croft, D., "Modelling of Wildlife Fatality Hotspots Along the Snowy Mountain Highway in New South Wales, Australia." *Biological Conservation*, Vol. 126 (2005) pp.474-490.

193. Ramp, D., Wilson, V. and Croft, D., "Assessing the Impacts of Roads in Peri-Urban Reserves: Road-based Fatalities and Road Usage by Wildlife in the Royal National Park, New South Wales, Australia." *Biological Conservation*, Vol. 129 (2006) pp.348-359.

194. Reed, D.F., Pojar, T.M. and Woodard, T.N., "Use of One Way Gates by Mule Deer." *Journal of Wildlife Management*, Vol. 38 (1974) pp.9-15.

195. Reed, D.,Woodward, T. and Pojar, T., "Behavioral Response of Mule Deer to a Highway Underpass." *Journal of Wildlife Management*, Vol. 39 (1975) pp.361-367.

196. Reeve, A.F., "Vehicle-Related Mortality of Mule Deer in Nugget Canyon, Wyoming." *Wyoming Cooperative Fisheries and Wildlife Research Unit Report*, Laramie, WY (1988).

197. Rei, W. and Seiz, A., "The Influence of Land Use on the Genetic Structure of Populations of the Common Frog *Rana temporaria*." *Biological Conservation*, Vol. 54 (1990) pp.239-249.

198. Renzhu, P., Zhang, M., Jialong, T. and Piao, C., "A Study of Winter Movement Characteristics for Wolverines in Daxinganling Mountains of China." *Acta Theriologica Sinica*, Vol.15 (1995) pp.209-214.

199. Rheindt, F.E., "The Impacts of Road on Birds: Does Song Frequency Play a Role in Susceptibility to Noise Pollution?" *Journal of Ornithology*, Vol. 144 (2003) pp.295-306.

200. Ripley, B.D., Spatial Statistics. John Wiley and Sons, NY (1981).

201. Romin, L.A. and Bissonette, J.A., "Deer-Vehicle Collisions: Status of State Monitoring Activities and Mitigation Efforts." *Wildlife Society Bulletin*, Vol. 24 (1996) pp.276-283.

202. Roof, J. and Wooding, J., "Evaluation of S.R. 46 Wildlife Crossing." *Florida Department of Transportation and the Florida Game and Fresh Water Fish Commission Technical Report # 54*, Tallahassee, FL (1996).

203. Rosell, C., "Measures Applied to Mitigate Habitat Fragmentation in Spain." International Conference on Ecology and Transportation, Lake Placid, NY, Proceedings (2003) p.204.

204. Ruediger, B. and Lloyd, J., A Rapid Assessment Process for Determining Potential Wildlife, Fish and Plant Linkages for Highways." International Conference on Ecology and Transportation, Lake Placid, NY, Proceedings (2003) pp.205-222.

205. Ruediger, B., Basting, P., Becker, D., Bustick, J., Cavill, P., Claar, J., Foresman, K., Hieinz, G., Kaley, D., Kratville, S., Lloyd, J., Lucas, M., McDonald, S., Stockstad, G., Vore, J., Wall, K., Wall, R., "An Assessment of Wildlife and Fish Linkages on Highway 93 - Western Montana." *Forest Service Publications #R1-04-81*, USDA Forest Service, USDI Fish and Wildlife Service, confederated Salish and Kootenai Tribe, Rocky Mountain Elk Foundation, Montana Fish, Wildlife and Parks, Montana Department of Transportation, Geodata Services, The University of Montana, Missoula, MT (2004) 41 pp.

206. Saeki, M. and. Macdonald, D.W., "The Effects of Traffic on the Raccoon Dog (*Nyctereutes procyonoides viverrinus*) and Other Mammals in Japan." *Biological Conservation*, Vol. 118 (2004) pp.559-571.

207. Schmidt, N.M., Berg, T.B. and Jensen, T.S., "The Influence of Body Mass on Daily Movement Patterns and Home Ranges of the Collared Lemming (*Dicrostonyx groenlandicus*)." *Canadian Journal of Zoology*, Vol. 80 (2002) pp.64-69.

208. Seiler, A., "Spatial Models to Predict Moose-Vehicle Collisions in Sweden." PhD Thesis, Department of Conservation Biology, Swedish University of Agricutural Sciences, Uppsala, Sweden (2003).

209. Seton, E.T., Life Histories of Northern Animals: An Account of Mammals in Manitoba. Scribner and Sons, NY (1909).

210. Sherwood, B., Cutler, D. and Burton, J.A. Wildlife and Roads: The Ecological Impact. Imperial College Press, London, England (2002).

211. Sielecki, L., "WARS Wildlife Accident Reporting System 2000 Annual Report (1991-2000 Synopsis)." *Environmental Management Section Report*, Engineering Branch, British Columbia Ministry of Transportation, Victoria BC Canada (2001).

212. Singleton, P., Gaines,W. and Lehmkuhl, J., "Landscape Permeability for Large Carnivores in Washington: A Geographic Information System Weighted-Distance and Least-Cost Corridor Assessment." *USDA Research Paper PNW-RP-549*, Pacific Northwest Research Station, U.S. Forest Service (2002).

213. Singleton, P.H. and Lehmkuhl, J.F., "Assessing Wildlife Habitat Connectivity in the Interstate 90 Snoqualmie Pass Corridor, Washington." International Conference on Wildlife Ecology and Transportation, Missoula, MT, Proceedings (1999) pp.75-84.

214. Singleton, P.H. and Lehmkuhl, J.F., "I-90 Snoqualmie Pass Wildlife Habitat Linkage Assessment." *USDA Forest Service Report WA-RD 489.1.*, Washington State Department of Transportation (2000).

215. Smith, D.J., Harris, L.D. and Mazzotti, F.J., "Highway - Wildlife Relationships: Developoment of a Decision-based Wildlife Underpass Road Project Prioritization Model on GIS Statewide Application." *Final Report to the Florida Department of Transportation*, Contract No. B-9943, University of Florida, Gainesville, FL (1998).

216. Snaith, T.V. and Beazley, K.F., "The Distribution, Status and Habitat Associations of Moose in Mainland Nova Scotia." *Proceedings of the Nova Scotian Institute of Science*, Vol. 42 (2004) pp.263-317.

217. Spitz, F. and Janeau, G., "Spatial Strategies: An Attempt to Classify Daily Movements of Wild Boar." *Acta Theriologica*, Vol. 35 (1990) pp.139-149.

218. Sprent, P., Applied Nonparametric Statistical Methods. Chapman and Hall, First edition (1989) 259 pp.

219. SPSS, SPSS version 11.0 for Windows. SPSS Inc., Chicago, IL (2004).

220. SPSS, SPSS version 11.0.1 for Windows. SPSS Inc., Chicago, IL (2006).

221. Steen, D.A. and Gibbs, J.P., "Effects of Roads on the Structure of Freshwater Turtle Populations." *Conservation Biology*, Vol. 18 (2004) pp.1143-1149.

222. Stenseth, N.C. and Lidicker, W.Z., Animal Dispersal: Small Mammals as a Model. Chapman & Hall, London, England (1992).

223. Stevens, V.M., Polus, E., Wesselingh, R.A., Schtickzelle, N. and Baguette, M., "Quantifying Functional Connectivity: Experimental Evidence for Patch-Specific Resistance in the Natterjack Toad (*Bufo calamita*)." *Landscape Ecology*, Vol. 19 (2004) pp.829-842.

224. Sullivan, T.P., Sullivan, D.S. and Hogue, E.J., "Population Dynamics of Deer Mice, *Peromyscus maniculatus*, and Yellow-pine Chipmunks, *Tamias amoenus*, in Old Field and Orchard Habitats." *Canadian Field-Naturalist*, Vol.118 (2004) pp.299-308.

225. Sulok, M., Slade, N.A. and Doonan, T.J., "Effects of Supplemental Food on Movements of Cotton Rats (*Sigmodon hispidus*) in Northeastern Kansas." *Journal of Mammalogy*, Vol. 85 (2004) pp.1102-1105.

226. Sutherland, G.D., Harestad, A.S., Price, K. and Lertzman, K.P., "Scaling of Natal Dispersal Distances in Terrestrial Birds and Mammals." *Conservation Ecology*, Vol. 4 (2000) pp.1-16.

227. Szemethy, L., Matrai, K., Biro, Z. and Katona, K., "Seasonal Home Range Shift of Red Deer in a Forest-Agriculture Area in Southern Hungary." *Acta Theriologica*, Vol. 48 (2003) pp.547-556.

228. Tabachnick, B.G. and Fidell, L.S., Using Multivariate Statistics.Harper Collins, NY (1996).

229. Thiel, R.P., "Relationship Between Road Densities and Wolf Habitat Suitability in Wisconsin." *American Midland Naturalist*, Vol. 113 (1985) pp.404-407.

230. Thompson, L.M., "Abundance and Genetic Structure of Two Black Bear Populations Prior to Highway Construction in Eastern North Carolina." Masters Thesis, University of Tennessee, Knoxville, TN (2003).

231. Trakhtenbrot, A., Nathan, R. Perry and Richardson, D.M., "The Importance of Long-Distance Dispersal in Biodiversity Conservation." *Diversity and Distributions*, Vol. 11 (2005) pp.173-181.

232. Transportation Research Board, "Environmental Research Needs in Transportation." TRB Conference, National Academy Press, Washington, DC, Proceedings Vol. 28 (2002).

233. Turchin, P., Quantitative Analysis of Movement. Sinauer, Sunderland, MA (1998).

234. United States General Accounting Office, "State and Metropolitan Planning Agencies Report Using Varied Methods to Consider Ecosystem Conservation: Report to Congressional Requesters." *GAO-04-536*, Washington, DC (2004).

235.   University of Massachusetts, Amherst., "Massachusetts River and Stream Crossing Standards: Technical Guidelines."(2004) url:http://www.umass.edu/nrec/onlinedocs.html

236.   Van Dyke, F.B., Brocke, R.H., Shaw, H.G., Ackerman, B.B., Hemker, T.P. and Lindzey, F.G., "Reactions of Mountain Lions to Logging and Human Activity." *Journal of Wildlife Management*, Vol. 50 (1986) pp.95-102.

237.   Vos, C.C. and Chardon, J.P., "Effects of Habitat Fragmentation and Road Density on the Distribution Pattern of the Moor Frog *Rana arvalis*." *Journal of Applied Ecology*, Vol. (1998) pp.44-56.

238.   Wagner, P., "Improving Mobility for Wildlife and People: Transportation Planning for Habitat Connectivity in Washington State." International Conference on Ecology and Transportation, San Diego, CA, Proceedings (2006) p.79.

239.   Wang, M. and Schreiber, A., "The Impact of Habitat Fragmentation and Social Structure on the Population Genetics of Roe Deer (*Capreolus capreolus* L.) in Central Europe." *Heredity*, Vol. 86 (2001) pp.703-715.

240.   Washington, S., Persaud, B., Lyon, C. and Oh, J., "Validation of Accident Models for Intersections." *Federal Highway Administration Report FHWA-RD-03-037*, Washington, DC (2005).

241.   Wayne, R.K., George, S.B., Gilbert, D., Collines, P.W., Kovach, S.D., Girman, D. and Lehman, N., "A Morphologic and Genetic Study of the Island Fox *Urocyon littoralis*." *Evolution*, Vol. 45 (1991) pp.1849-1868.

242.   Weigel, L., "Results of a National Opinion Poll Conducted for the International Association of Fish and Wildlife Agencies to Ascertain the American Public's Perceptions and Values of Wildlife." American Conservation Information Conference, Ogden, UT, Proceedings (2005).

243.   White, G.C. and Burnham, K.P., "Program MARK: Survival Estimation From Populations of Marked Animals." *Bird Study*, Vol. 46 Supplement (1999) pp.120-138.

244.   Wiens, J.A., "Spatial Scaling in Ecology." *Functional Ecology*, Vol. 3 (1989) pp.385-397.

245.   Wiens, J.A., "The Landscape Context of Dispersal." *Dispersal*, Oxford University Press, NY (2001) pp.96-109.

246.   Williams, B.K., Nichols, J.D. and Conroy, M.J., Analysis and Management of Animal Populations. Academic Press (2001) 817 pp.

247.   Wolff, J.O., "Behavioral Model Systems." *Landscape Ecology of Small Mammals*, Springer (1999) pp.11-40.

248. Worton, B.J., "A Review of Models of Home Range for Animal Movement." *Ecological Modelling*, Vol. 38 (1987) pp.277-298.

249. Zalewski, A., Jedrzejewski, W. and Jedrzewska, B., "Mobility and Home Range Use by Pine Martens (*Martes martes*) in a Polish Primeval Forest." *Ecoscience*, Vol. 11 (2004) pp.113-122.

250. Zar, J.H., Biostatistical Analysis. Third Edition. Prentice Hall, Upper Saddle River, NJ (1996) 662 pp.

251. Zar, J.H., Biostatistical analysis. Fourth Edition. Prentice Hall. Upper Saddle River, NJ (1999).

APPENDICES

Appendix A: Priority Tables and Plan of Action

Top Five Practice Priorities by Nation

Table 39: Top 5 priorities for restoring wildlife movement across roads in the United States and Canada

United States Top Priorities	Rank	Canada Top Priorities
Incorporate wildlife mitigation needs **early** in the DOT/MoT programming, planning, and design process	1	Same
Combine animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than using one method	2	Same
Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out	3	Same
Establish effective communication and collaboration among stakeholders	4	Use standardized and vetted protocols for collecting and recording road kill carcass and wildlife-vehicle colllision data
Incorporate into plans and schedules wildlife crossing options that can be accomplished by maintenance crews simply by retrofitting existing facilities	5	Establish effective communication and collaboration among stakeholders

Top Five Research Priorities by Nation

Table 40: Top 5 research priorities for restoring wildlife movement across roads in United States and Canada

United States Top Priorities	Rank	Canada Top Priorities
Understand better the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information	1	Same
Develop and summarize alternative, cost effective wildlife crossings designs and the principles they are based on	2	Standardize spatially accurate road kill carcass and wildlife-vehicle colllision data collection
Develop wildlife crossing structure designs and guidelines for the full suite of animals in an area to help facilitate permeability for many species	3	Develop and summarize alternative, cost effective wildlife crossings designs and the principles they are based on
Develop state-based habitat connectivity analyses for every state	4	Develop guidelines to decide when wildlife mitigation is necessary (both mandated and voluntary)
Develop a standardized monitoring protocol to assess crossing effectiveness	5	Develop prototype animal/vehicle collision safety models to predict where wildlife-vehicle colllision "hotspot" areas are and may be on future roads

Top Five Practice and Research Priorities for Engineers/Analysts/GIS Professionals

Table 41: Top 5 research and practice priorities for Engineers/Analysts/GIS specialists

Rank	Practice Priorities
1	Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process
2	Establish effective communication and collaboration among stakeholders
3	Combine animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than using one method
4	Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out
5	Incorporate into plans and schedules wildlife crossing options that can be accomplished by maintenance crews simply by retrofitting existing facilities

Rank	Research Priorities
1	Understand better the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information
2	Develop and summarize alternative, cost effective wildlife crossings designs and the principles they are based on
3	Develop guidelines to decide when wildlife mitigation is necessary (both mandated and voluntary)
4	Develop a standardized monitoring protocol to assess crossing effectiveness
5	Develop wildlife crossing structure designs and guidelines for the full suite of animals in an area to help facilitate permeability for many species

Top Five Practice and Research Priorities for Planners

Table 42: Top 5 research and practice priorities for Planners

Rank	Practice Priorities
1	Combine animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than using one method
2	Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process
3	Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out
4	Incorporate into plans and schedules wildlife crossing options that can be accomplished by maintenance crews simply by retrofitting existing facilities
5	Establish effective communication and collaboration among stakeholders

	Research Priorities
1	Understand better the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information
2	Develop and summarize alternative, cost effective wildlife crossings designs and the principles they are based on
3	Develop wildlife crossing structure designs and guidelines for the full suite of animals in an area to help facilitate permeability for many species
4	Develop standardized inventories of wildlife crossings by state for better management and maintenance of these crossings, and to better assess the need for future crossings*
5	Three priorities tied for fifth rank: a) Develop a standardized monitoring protocol to assess crossing effectiveness & b) Develop guidelines to decide when wildlife mitigation is necessary (both mandated and voluntary) c) Increase our understanding of the effects of road density on wildlife populations*

Top Five Practice and Research Priorities Natural Resource Professionals – Overall

Table 43: Top 5 research and practice priorities for Natural Resource Professionals

Rank	Practice Priorities
1	Incorporate wildlife mitigation needs early in the DOT/MoT programming, planning, and design process
2	Combine animal-friendly mitigation methods such as wildlife crossing structures, fences, escape ramps and gates, rather than using one method
3	Use conservation plans and connectivity analyses to inform the transportation programming/planning/design process on where mitigation is needed and how it may be carried out
4	Establish effective communication and collaboration among stakeholders
5	Incorporate into plans and schedules wildlife crossing options that can be accomplished by maintenance crews simply by retrofitting existing facilities

	Research Priorities
1	Understand better the dynamics of animal use of mitigation structures (such as what works and what doesn't) and disseminate this information
2	Develop and summarize alternative, cost effective wildlife crossings designs and the principles they are based on
3	Develop wildlife crossing structure designs and guidelines for the full suite of animals in an area to help facilitate permeability for many species
4	Develop state-based habitat connectivity analyses for every state
5	Develop a standardized monitoring protocol to assess crossing effectiveness

Plan of Action for Priorities

Practice Gaps and Priorities

Ecological

Agencies responsible for creating wildlife mitigation measures along transportation corridors would profit by standardizing and institutionalizing practices that aid in the development of mitigation techniques.

There is a need to standardized methods for collecting and recording data, the development and communication of state and provincial wildlife habitat conservation needs, and the development of wildlife crossing structure guidelines on state- and province-wide and regional bases. When transportation professionals and scientists seek readily available databases or systematic methodologies for gathering data so that they can incorporate ecological data into transportation programs or mitigation models and measures, they are apt find that long-term databases, such as those containing wildlife-vehicle colllisions data are usually not associated or linked with spatially accurate locations, road geometrics, or environmental data. Additionally, databases may be in a variety of formats. For example, wildlife-vehicle colllisions data is contained in highway patrol reports, and in forms filled out by highway maintenance crews. Important data such as the location and maintenance schedules for culverts and bridges is not always electronically available. There are also inconsistencies among states and provinces concerning the dissemination of critical wildlife habitat needs, and the identification of priority areas for conservation. If these data were readily available in electronic databases similar to each state's Natural Heritage program but in greater detail, DOTs and MoTs would be better able to incorporate wildlife and ecosystem priorities into the planning stages of transportation programs and individual projects. Additionally we found that guidelines for planning and installing wildlife crossing structures are nonexistent for most states and provinces. In summary, we have found a lack of: 1) long-term and accurate databases on wildlife-vehicle colllisions or road kill carcass locations that are electronically based and standardized; 2) a nation-wide standardized method for state and provincial wildlife agencies to incorporate wildlife locations and their habitats and needs in a cohesive document readily available for other agencies to work with and 3) widely available guidelines for developing and maintaining wildlife crossing structures and other mitigation measures. Without standardized and institutionalized practices informed by accurate, complete, and documented databases, transportation professionals find it difficult to collect and analyze data on wildlife-vehicle crashes and road kill carcass locations, include ecological and safety data into the planning process, create mitigation measures for wildlife, or find ways to integrate existing maintenance and upgrade schedules with mitigation opportunities.

Priority

Create standardized protocols for collecting road kill carcass locations and wildlife-vehicle colllision data. This information is crucial in helping to determine where wildlife mitigation measures to reduce wildlife-vehicle colllision are needed.

Departments and Ministries of Transportation would benefit from the collection of data by standardized, accurate methods that could be incorporated with future road improvements, road building, and reductions in wildlife related crashes. (See priorities above under safety models). We point to two successful efforts: Maine has an wildlife-vehicle colllision reporting program that is geo-referenced and mapped for the public (Maine DOT 2002), and British Columbia has maintained a long term database of wildlife-vehicle colllisions that is analyzed in order to create appropriate measures to reduce these crashes (Sielecki 2001).

Priority

Create continent-wide guidelines and standards for determining when during the transportation planning process agencies should assess programs and projects for wildlife needs. The U.S. Transportation Equity Act for the 21st Century (TEA-21) requires that planners develop long range plans and short-range programs that consider projects and strategies that among other things will protect and enhance the environment. However, the act provides no guidance on how planners should meet these requirements (GAO 2004). Typically if ecosystem and wildlife are considered, it is late in the development of a transportation project. This can often lead to delays in the permitting process, incurring the expenditure of additional funds. This is not in the best interest of the ecological resource, the transportation agencies, or the public. We strongly suggest these analyses be incorporated early in the development of long range transportation plans. Planners in Oregon, South Dakota, Colorado, and North Carolina for example, extensively consider ecosystem conservation during planning processes (GAO 2004). Vermont has a policy of addressing wildlife and fish needs in future transportation projects prior to regulatory intervention (C. Slesar and J. Austin personal communication) and Montana state and federal agency personnel have worked together to create the largest, most comprehensive sets of wildlife mitigation measures over one highway in the United States (Ruediger et al. 2004). This priority is linked with the priorities to implement statewide connectivity analyses, enacting policy to mandate these actions, and the priority below, the development of statewide wildlife habitat conservation plans.

Priority

Incorporate state- and province-wide maps and conservation plans for critical wildlife habitat needs into transportation planning. The U.S. Fish and Wildlife Service has asked state wildlife agencies to complete their wildlife habitat conservation plans by October 2005. These plans will include GIS generated maps showing ranges and critical habitats of species of concern and will greatly assist DOTs and MoTs in planning mitigation to maintain or restore ecosystem integrity and viable wildlife populations. We may use the successes of current programs to help guide our actions. For instance, Florida's Fish and Wildlife Commission has communicated wildlife needs through their Integrated Wildlife Habitat Ranking System (Endries et al. 2003), the 'Closing the Gaps in Florida's Wildlife Habitat Conservation System' documentation, their statewide 'Strategic Habitat Conservation Areas' program, and the 'Biodiversity Hot Spots' which are all scientific efforts that are translated into GIS data layers and are incorporated into

Florida DOT's Environmental Screening tool (V. Sharpe personal communication, Florida Fish and Wildlife Commission 2004).

Priority

Create and update guidelines for considering, placing, designing, and constructing wildlife crossing structures. This is a priority for the practice as well as the science of road ecology. This priority is linked to the development of monitoring programs to assess the effectiveness of mitigation measures (Hardy et al. 2003). More detailed statements related to this priority can be viewed above under guidelines in research priorities. Examples of current guideline efforts include: the set of guidelines created for the installation of amphibian and reptile tunnels in New England (Jackson 2003), standards created for river and stream crossings for fish (University of Massachusetts 2003), and Colorado's guidelines for the placement of crossing opportunities for wildlife (Barnum 2003). We have and will continue to learn from one of the agency leaders in wildlife crossing structures, Parks Canada, who has taken the lead for the North American continent in instituting and evaluating wildlife crossing structures.

Priority

Funding and maintenance for an outlet that communicates the standardized guidelines is a priority. Guidelines could be communicated and updated through the use of agency-based websites. As our knowledge improves and evolves, so should the guidelines be updated to reflect this or they risk becoming obsolete. There is a need for meaningful partnerships among federal agencies and associations to commit resources and personnel to maintain useful websites. Ideally, these sites should provide extensive searchable literature databases, annotated bibliographies, research reviews linked to projects, as well as the above mentioned guidelines, and any decision tool associated with the NCHRP project (NCHRP 25-27) currently in progress. Linking to existing websites, i.e., the Wildlife Crossings Toolkit, the Deer-Vehicle Crash Information Clearinghouse would be most helpful. In the coming two years, our project (NCHRP project 25-27) will address these concerns. This is an ongoing priority that needs the continued guidance and attention from a multi-agency committee that has credibility with transportation professionals.

Priority

Maintenance activities on crossing structures need to be recorded in standardized documentation schedules. If structures and accompanying mitigation features such as fences are not maintained, their effectiveness often decreases (Dodd et al. 2004A). Documentation of maintenance schedules, methods, and costs provide assurance that the structures are fulfilling their purpose, and can help in establishing maintenance needs for future mitigation measures.

Priority

Create alignment specifications for effective mitigation efforts that link wildlife crossing structures with fences and Right-Of-Way (ROW) escape ramps. We know certain fence types are not wildlife friendly and that wildlife need to be able to escape if trapped on the roadway. Evidence from studies conducted at Utah State University suggest that the rectangular mesh design used in most 'deer-proof' fencing applications can result in the death of juvenile animals who become trapped in the fence. The barbed wire arrangement used in lower fences is also problematic for species such as pronghorn antelope. We urge standards for animal friendly fences, for example, a different mesh size for exclusion fences. Larger animals often access the ROW even if it is fenced. Measures (such as earthen escape ramps) are needed to allow them to escape the road right-of-way in the presence of exclusion fencing. Fencing mitigation efforts need to incorporate escape ramps in order to be maximally effective. Ungulate (deer, elk, and moose) are much more inclined to use escape ramps than 'squeeze-through' steel gates to escape the right of way. Additionally, in areas with rugged topography, the typical perpendicular ramp-fence alignment may not be most effective. Ramps placed 'in-line' with the fence may be a desired alternative. There is a need to explore other escape mechanisms that could be created for large and small animals, e.g., badger and small mammal tunnels. We also encourage the practice of implementing alternative and innovative designs. These could be developed in an adaptive management context of learning from doing; a context where practice is tied to research in an explicit fashion. This approach is currently in use in developing wildlife mitigation measures in Arizona (Dodd et al. 2004B). For small animals that are not deterred by exclusion fences, we suggest the adoption of jersey barriers with wildlife scuppers (openings in the barrier that allow for small animal and water movement passage), or low barriers that direct animals to small tunnel-like passages. Additionally, research has shown higher road kill levels often occur at the end of the fenced mitigation, the so called 'end-of-fence' problem (Dodd et al. 2004). We consider it a priority to address fence designs, the end-of-fence problem, and ramp-fence alignments in order to increase the effectiveness of these common mitigation structures.

Priority

Culvert and bridge maintenance schedules need to be made available in electronic format so upgrade and replacement projects can be coordinated with mitigation measures. Existing transportation infrastructure could be retrofitted for wildlife and fish during routine maintenance and upgrading. Regional protocols could be developed to integrate culvert, bridge, and fencing maintenance schedules with the needs of aquatic and terrestrial wildlife in the area. Protocols that retrofit culverts for fish passage are in available in several states (i.e.,-Bates 2003, Maine Department of Transportation 2004, McIninch and Garman 2004).

As we learn more about efforts by states and provinces to create standardized collection methods and data storage, and to create guidelines for wildlife mitigation measures, we believe these efforts can be implemented across the continent.

Policy and Planning

National, state, and provincial authorities at the highest levels need to be fully engaged if policies and guidelines that mandate the use of standardized and effective methods to maintain and promote permeability and connectivity of the landscape for wildlife are to be enacted.

If transportation and natural resource agencies continent-wide are to address the pressing issues of landscape fragmentation and effects of road transportation networks on species, we must go beyond the individual transportation projects and individual species approaches of the past (Foreman et al. 2003). There is a need for national level, firm, and legal guidelines that mandate the incorporation of wildlife and ecosystem considerations early in the long range transportation planning stage. There is also a need to correct the basic inconsistencies among states and provinces in their practices and policies toward protecting wildlife and re-establishing connectivity across the landscape. To this end it is necessary to establish common goals and objectives that state/provincial and federal governmental agencies can agree upon and accomplish in order to increase permeability of transportation corridors for wildlife.

Priority

Legislation that enables and funds mandatory planning and mitigating for wildlife along transportation corridors is desirable. We believe this is attainable and point to two currently successful programs: Florida and The Netherlands. In both places, laws and policies have been passed and programs funded to develop maps of ecological networks and to identify places where roads fragment or fracture these networks, and where specific areas and transportation projects for mitigation and compensation have been identified (Bank et al. 2002, Foreman et al. 2003). In order for similar actions to be applied across the United States and Canada, there is a need for fully funded federal level mandates or strong incentive programs that authorize and institutionalize methods to identify, plan, and mitigate for landscape connectivity along transportation corridors. Funding for this effort may be attained from TEA-21, FHWA research funds, and dedicated state funds (Banks et al. 2002, Evink 2002A).

We suggest that leadership for these efforts to coordinate multi-agency standards that help maintain and promote permeability and connectivity of the landscape for wildlife come from a strong federal-state/provincial partnership. Likely partners include the U.S Federal Highway Administration (FHWA) and Transport Canada as well as the U.S. Fish and Wildlife Service and Environment Canada, coupled with transportation and wildlife representatives from the states and provinces. Additional organizations might well include the American Association of State Highway and Transportation Officials (AASHTO), the U.S. Forest Service, the Environmental Protection Agency, and the Bureau of Land Management (Bank et al. 2002). NGO participation would provide a public input and several have been active in this arena (Defenders of Wildlife, the BC Conservation Foundation, and The Nature Conservancy). A successful partnering arrangement might partition duties with wildlife and natural resource agencies providing ecological guidelines as well as measures of success, while the FHWA and Transport

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Canada could standardize and coordinate compliance with state and provincial D/MOTs, while at the same time linking incentives with funding.

We strongly encourage funding incentives in these mandates for transportation agencies to: 1) conduct connectivity studies, for example, as Washington State DOT has done (Singleton et al. 2002), 2) fund GIS data development (which many D/MOTs have done), 3) continue data-partnering with other agencies which most states do but which can be improved (Fletcher 2004), 4) incorporate wildlife habitat connectivity maps in long range transportation program planning such as Washington and Florida have done, 5) mitigate for wildlife in most transportation projects (e.g., such as what is done in Vermont), and 6) remain consistently committed to this goal over time. Such a specifically defined approach would help to level the current inconsistencies among states and provinces and promote continent-wide permeability for wildlife across transportation corridors.

Communication

Improved communication among transportation professionals, on-the-ground transportation workers, scientists, activists, and the public is needed to help insure that wildlife crossings measures and other actions to maintain ecosystem permeability across transportation networks are driven by the most effective and efficient methodologies.

Road ecology is a rapidly developing field of study that relies on communication among researchers and practitioners from around the world. While great gains have been made in this field in the past 10 years, we have observed common gaps in communication within and among agencies and other professionals and the public that directly affect the ability to place and maintain wildlife crossing structures. It is imperative that study results and practices that are both successful and unsuccessful are communicated as quickly and effectively as possible in order for transportation planners and engineers to build transportation corridors that are less damaging to wildlife. Although not universal, the lack of communication and data sharing among agencies at federal and state levels that relate to long range planning, the collection of accurate road kill and wildlife-vehicle colllision locations, and the effective placement, construction, monitoring, and maintenance of mitigation structures hampers progress. Additionally the lack of funding to coordinate such communication is problematic.

The need for communication has been a common theme in the priorities listed in this document. We find it is a key component to successful wildlife mitigation programs. The most successful and far reaching wildlife-transportation mitigation programs across the U.S. and the world have communications networks (such as the Infra Eco Network Europe or IENE) that have been developed to: coordinate information (Fletcher 2004), include ecosystem level needs in transportation planning (IENE's Cost 341 effort, Iuell et al. 2003), and garner support for providing measures for wildlife in transportation systems (Bank et al. 2002). From these and other examples of successes within states

and provinces, we describe below two priorities that relate to informal and formal communication.

Priority

Informal communication opportunities must be increased among transportation professionals, on-the-ground transportation workers, and ecologically trained professionals. Some notable successes include the International Conference on Ecology and Transportation bi-annual events and the well circulated proceedings from those conferences, the Center for Transportation and the Environment at North Carolina State and its well maintained website and list server, the Wildlife Crossings Toolkit website initiated by the U.S. Forest Service and housed at Utah State University, the Deer-Vehicle Crash Information Clearinghouse at the University of Wisconsin, and other events, publications and website dedicated to highlighting and exploring wildlife and transportation issues. We encourage transportation and wildlife professionals to communicate using the above mentioned methods and other less formal means to learn about ecological impacts of roads, successes and failures of research and practices, innovative ideas, and for increased opportunities to include wildlife and ecosystem needs into the planning and designing of roads. Increased communication opens opportunities to coordinate mitigation for ecosystem and wildlife needs in the development of long range programs and project plans long before these plans became fully developed and budgeted. There is a strong need for direct communication between biologists and on-the-ground transportation workers. These workers are the critical link to accurate data collection and are often the source of innovative design solutions. They are often very interested in wildlife and would like feedback on the effectiveness of mitigation measures that they design and install. They can also provide crucial information to biologists such as maintenance schedules for bridges, culverts, and upgrades to roads. If these schedules were coordinated with environmental managers and biologists, ideally these already planned projects could present opportunities to retrofit these structures for the movement of wildlife, fish, and ecological processes. With over 575,000 bridges in the U.S. and as many as 40,000 of these will need repair or replacement in the next two decades (McDonald and Smith 1999), there are literally tens of thousands of opportunities to coordinate such efforts to improve landscape connectivity.

Priority

Increase formal communications among states, provinces, and countries. We believe these communications are necessary to help this field move forward concerning the development of effective mitigation structures. There are several avenues for increased communications including: clearinghouses, conferences, proceedings, publications, and federally sponsored websites such as FHWA's Exemplary Ecosystem Initiatives and Wildlife Protection – Keeping it Simple, the Transportation Research Board's Transportation Research Information Services database, AASHTO's Center for Environmental Excellence, and Standing Committee on the Environment, British Columbia Conservation Foundation's Wildlife Vehicle Accident Prevention Program, and Parks Canada's Highway Mitigation Research Program. We suggest a clearinghouse for projects across North America. This central location could be maintained by the

Federal Highways Administration and would house information on past, current, and future projects with specifics that would be of interest to other agencies and locations. We suggest additional opportunities to share information over the entire continent for example increasing the number of public meetings such as ICOET and regional ecology and transportation conferences, for instance the Northeast Wildlife and Transportation Conference. The proceedings of these meetings are a major source of information on developments in this field. The proceedings and other information could be published in a way that professionals from a variety of non-ecological transportation interests such as planners, administrators, and engineers, would be notified electronically of their existence. These proceedings and other publications would help promote the science base of road ecology if they gave easily accessed sets of definitions for all professionals to understand. Communication could also be improved if long term funding was available to maintain websites dedicated to wildlife crossing structures and other related mitigation measures. Linking them to the Federal Highways Administration website is a step in the right direction. Finally, professionals have a responsibility to educate and help the public become aware of issues concerning wildlife mortality, crossing structures, landscape fragmentation versus permeability, and public safety. We encourage transportation agencies to communicate with the public the needs for wildlife crossings projects, the development and completion of mitigation measures, and the results of monitoring projects. In these communications we strongly encourage scientific messages pertaining to the issues of fragmentation and connectivity to help the public understand. We encourage progress in all these areas in order to quickly and efficiently bring about change in the practices associated with transportation and wildlife.

Research Gaps and Priorities

Safety

Existing wildlife-vehicle colllision prediction models require further development to be effectively used for safety analyses tasks such as identifying wildlife collision prone locations on both existing roads and new roads, evaluating the collision reduction effectiveness of mitigation measures, and conducting cost-effectiveness analyses of potential mitigation projects.

There is a need for the development of more reliable wildlife-vehicle colllision prediction models that would inform transportation professionals about collision-prone areas, not only on existing roadways, but also on new roadways in the planning or design stage. These models would assist in systematic screening of the road network, which is routinely done in jurisdictions[1], in order to identify specific locations which merit further investigation as potential locations for crossing structures, fencing, and other mitigation measures such as those that address driver behavior (e.g. reduced speed limits). These same predictive models are also required to assess, retrospectively, the collision reduction effectiveness of countermeasures aimed at reducing wildlife-vehicle colllisions. The types of models required for these purposed ideally would estimate the *expected frequency of collisions*. Most current site-specific models estimate the *probability of a site being a "high collision location,"* which is subjectively defined, and therefore does

not provide an estimate of the expected collision frequency (Bashore et al. 1985, Finder 1997, Hubbard et al. 2000). These "probability" models typically include variables which necessitate field data collection and thus they cannot be applied for network–wide screening due to data limitations in state databases (Meyer and Ahmed 2004). Additionally, most current wildlife-vehicle colllisions prediction models are limited in their ability to accurately describe the general cause-and-effect relationships among variables that affect collisions and hence are limited in their ability to inform practitioners who would like to be proactive in predicting where wildlife-vehicle colllisions are most likely to occur. The development of integrated models is hampered by: 1) the lack of a national protocol for collecting wildlife-vehicle colllision as well as road kill carcass data; 2) the limited number of reliable long-term databases of wildlife-vehicle colllisions and road kill carcass data; 3) the lack of crash site data or other important model inputs such as highway variables (geometrics) and ecological variables (e.g., topography and existence of migration routes); and 4) the lack of knowledge of wildlife exposure (i.e., the change over time of the number or density of animals in close enough proximity to a road to be potentially struck by a motor vehicle). It is apparent (to us) that spatial accuracy should be a defining characteristic of these data bases. We believe tremendous progress can be made in this research area if the following priorities can be accomplished.

Priority

Develop a strategic plan that is a well defined, interdisciplinary, and multi-jurisdictional strategy to address the wildlife-vehicle colllision problem and its complexities (Knapp 2004). There are dozens of attempts to model wildlife-vehicle colllisions with different methods, in different regions over many different situations, and yet the approaches tend to be piecemeal rather than building on one another. In order to bring the development of wildlife-vehicle colllision predictive models to a level where they are applicable over large regions, the combined efforts of professionals in several disciplines is desirable. We believe that the current pooled fund proposal (Knapp 2004) for the creation of a Deer-Vehicle Crash Information and Research Center is a step in the right direction for bringing the past and future work together in one central location and for the development of a cohesive strategy to address this issue.

Priority

Standardize and improve the collection of road kill carcass data and wildlife-vehicle colllision data. Data on road kills and wildlife-vehicle colllisions are currently collected by a variety of methods. We know of only one database that has the spatial accuracy needed to produce reliable ecological models that link environmental variables with road mortality of animals (the Parks Canada database). We suggest a road kill collection protocol and an wildlife-vehicle colllision location protocol be standardized across the nations or within regions in order to obtain spatially accurate reliable databases not only for modeling efforts, but also to assist in state Departments of Transportation (DOTs) and provincial Ministries of Transportation (MoTs) efforts to reduce collisions and road kill. Data collection on collision and carcass sites could provide more accurate information if they were geo-referenced, i.e., identified with Global Positioning Systems

(GPS) which accurately specifies the collision-carcass location. These accurate locations are critical if we are to assess the entire suite of other factors believed to affect collisions.

Priority

Include spatially accurate information on off-roadway variables into highway safety models used to predict wildlife-vehicle colllisions. If these data are not available, safety models could only be developed with only information pertaining to roads (road geometrics and traffic volumes). Such models, though still useful as predictive models, are limited in their ability to advance our understanding and capability to predict where and when wildlife-vehicle colllisions will occur. Off road information that would be considered in a model include variables known to affect wildlife movement across roads, such as: presence of nearby fencing, culverts and bridges, presence and characteristics of wildlife underpasses, adjacent land cover, distance to cover from the edge of the road, topography, human use of the area, species present, and standard road geometrics. We believe that assembling information on variables such as these would provide much improved databases that could in turn be used to improve our understanding of the causes of wildlife-vehicle colllisions and result in models that reflect this understanding and recommendations that would reduce these collisions and wildlife road kill in general.

Priority

Create standardized electronic inventories of existing crossing structures, bridges, and culverts and their geo-referenced locations in order to evaluate their potential for use by wildlife. Wildlife use crossing structures that are intended for them as well as transportation infrastructure such as culverts and bridge underpasses in order to avoid motor vehicles. Modelers, engineers, and biologists alike would be better able to distinguish between the need for additional crossing structures or mitigation measures vs. the modification of existing structures if there were state- and province-based electronic inventories of existing structures (culverts, underpasses) that could be analyzed as part of a safety model for their potential and current use by wildlife.

Priority

Develop methods to estimate the densities of animals near transportation corridors in order to calculate the risk of collision or exposure for certain stretches. We realize that calculating 'exposure' is a daunting task, and that surrogate measures, such as species density, daily movement behavior, seasonal migration patterns, annual harvest records (see Mysterud 2004) , and behavior near roads would need to be linked with spatial landscape data to approximate 'exposure.' This priority would entail working with state wildlife agencies in estimating and mapping where the most "high risk" animals are, i.e., deer, elk, and moose.

Priority

Develop research guidelines on evaluating the effectiveness of wildlife crossing structures from a vehicle-animal collision perspective. The guidelines should

demonstrate proper analysis methods and provide guidance on the monitoring of treatment sites. Monitoring of wildlife crossing structures should include data on pre- and post-construction wildlife-vehicle colllisions and road kills. In order for models to evaluate the effectiveness of the full suite of wildlife crossing structures measures, monitoring efforts of these crossing structures measures need to be expanded. When crossing structures are installed, monitoring efforts have typically focused on documenting the number of animals and species using the structures. We suggest that monitoring programs also include an analysis that documents pre and post construction wildlife-vehicle colllisions, road kill carcass data, traffic volume, and possible wildlife exposure. Proper analysis methods need to account for numerous difficulties in analyzing collision data including regression-to-the-mean effects, spillover effects, differences in accident investigation and reporting practice between jurisdictions when amalgamating data and exposure changes between before/after periods.

Cost-effective designs for wildlife crossing structures need to be developed through research and novel on-the-ground practices.

An analysis of cost-effectiveness is a requirement for the consideration of most mitigation measures for wildlife. If we could create flexible standards or 'standardized option-enabled' procedures and innovative designs, there would be more opportunities to incorporate wildlife mitigation measures in transportation projects. The term 'standardized option-enabled' means a general, clearly defined procedure or design with options so it can be modified to fit local situations. Currently it is difficult to link ecological values with safety values of wildlife mitigation measures for roads. Standardized procedures need to be developed for combining the estimated monetary costs of proposed wildlife crossing structures with ecological, safety, regulatory streamlining, and amortized monetary benefits. Standardized procedures would allow state and provincial departments and ministries of transportation to better evaluate how, what, and where to establish mitigation measures for wildlife in developing transportation programs and projects.

Priority

Develop standardized procedures for estimating monetary costs and ecological, safety, regulatory streamlining, and amortized monetary benefits. Researchers in ecological fields need to work with economic researchers to better estimate the economic benefits of wildlife, intact ecosystems, and ecological processes. These values, once standardized in some manner, could then become part of cost-benefit analyses of mitigation measures. These analyses also need to include the amortized monetary benefits to society of reduced wildlife road kill and vehicle collisions. These benefits would include reduced monetary costs to public agencies, insurance companies, medical and personal costs to motorists, and increased wildlife populations available for recreational opportunities such as hunting and bird watching. The economic benefit of including wildlife crossing structures early in project planning must also be taken into consideration, for this approach can streamline environmental regulatory processes, thereby reducing overall project cost. Once these monetary benefits of mitigation

measures are justified and standardized, a more realistic representative cost-benefit analysis method could be developed and employed across regions.

Priority

Develop innovative and economically viable 'option-enabled' alternative crossing designs after conducting standardized cost-effective procedures. Although there are dozens of wildlife crossings designs available, there are a standard dozen or so in most common use. Through research and practice, option-enabled alternatives could be explored that may allow added permeability of the landscape over and under transportation corridors, while at the same time minimizing costs incurred.

Ecological Considerations

The genetic implications of the effects of roads on populations are largely unknown but theoretical and empirical evidence suggests that they fragment populations and their habitats.

Transportation corridors are affecting the genetics of wildlife populations and we are just beginning to understand some of the consequences. There are a multitude of costs for wildlife associated with roads, from direct effects such as collision-caused mortality and habitat fragmentation, to indirect effects such as decreased reproductive success and road avoidance. There are data that suggest the barrier effects of the roaded landscape reduce permeability of those areas for wildlife populations. Several studies have demonstrated that roads may act as barriers to small mammal movements (Oxley et al. 1974, Barnett et al. 1978, Mader 1984) and as filter-barriers to large mammal movements (Beringer et al. 1990, Gibeau 2000). Roads can be complete barriers to individuals who cannot make their way across and whose road related mortality can affect their small populations. This is especially true for populations of wide-ranging carnivores who are particularly vulnerable to road traffic accidents (Florida panther *Puma concolor coryi*, Maehr et al. 1991; ocelot *Leopardus pardalis,* Hewitt et al. 1998; puma *Puma concolor,* Beier & Barrett 1993; Iberian lynx *Lynx pardalis,* Ferreras et al. 1992; and wolves *Canis lupus,* Fuller 1989). These effects over time will cause wildlife populations to suffer reduced sizes, isolation, skewed sex ratios (turtles, Steen and Gibbs 2004), depleted gene pools and even extirpation. Indeed, concern has been raised regarding the influence of highways on normal mammalian distributional patterns and perhaps ultimately on speciation (Baker 1998).

For all that we do know there are still tremendous gaps in our understanding of just how the genetics of populations are being affected by the fragmenting and isolation effects of roads (Rei and Seiz 1990). The barrier-effect of roads may reduce wildlife movement to the point of isolation, thereby reducing gene flow and increasing inbreeding and genetic drift (Ashley and Wills 1987, Wayne et al. 1991). Current literature supports such theories that roads are causing genetic consequences for a variety of species. These species include wide-ranging grizzly bears (*Urus artos*, Proctor et al. 2002, 2003) and black bears (*Ursus americanus*, Simek and Eason 2003, Thompson 2003), to smaller localized species including beetles (Keller et al. 2003) mice and shrews (Mills and

Conrey 2003) voles (Gerlach and Musolf 2000), frogs (Reh 1989), These and other studies indicate that research into the effects of genetic isolation due to transportation corridors must be promptly put in place to begin understanding the consequences of roads and to mitigate their effects.

Priority

Continue to study the genetic consequences of roads on wildlife. This research may most prudently be focused on: wide ranging species, small movement species, isolated populations, carnivores, amphibians, reptiles, and small mammals. Directed research efforts into the restriction of movement and its genetic effects would help define the needs for freedom of movement for the target species. Elimination of barriers to movement is essential for individual reproductive fitness and survivorship and has population consequences. Genetic research will help to define these movement needs, the necessary road crossing rates, and potential for appropriately designed wildlife crossing structures to help continue this flow. We argue that research will demonstrate that maintaining permeability of the landscape for a multitude of species will help negate the impacts of roads.

There is a need for long and short-term research targeted at assemblages of species to ascertain their reactions and behavioral adaptations over time to roads and associated mitigation features. This research will inform the development of 'option-enabled' general crossing designs that accommodate a wide range of species' requirements.

There is an urgent need for knowledge that would help in the design of wildlife crossing structures that allow the *full range of wildlife species* to move across and underneath transportation corridors. Information concerning behavioral reactions to roads and adaptations to crossing structures is lacking for most individual species, but particularly for species' reactions in an associated community (Clevenger and Waltho 2005). For instance, even though we may design mitigation measures for specific wide ranging and fragmentation-sensitive species (e.g., example grizzly bear and lynx, *Lynx canadensis*) we still do not have sufficient design data to develop crossing structure guidelines for many of these species (Evink 2002 A, Clevenger and Waltho 2000, 2005), much less suites of other species associated with the target species. Prior to developing guidelines for appropriate mitigation measures we must have a better understanding of roads effects on suites of species. To date there are relatively few studies of population-level and/or assemblage-level effects of roads. The existing studies suggest that the impacts can be significant. Findlay and Houlahan (1997) found significant effects of road density on species richness of wetland amphibian and reptiles, birds, and vascular plants. Fahrig et al. (1995) and Vos and Chardon (1998) found that presence/absence as well as density of local amphibian populations can be affected by road traffic. Forman et al. (2002) found decreased avian distribution and breeding near roadways in direct proportion to the volume of traffic on those roads.

There are several groups of species for which there is a paucity of research and whose needs have not been adequately addressed. Work is limited for carnivores and small mammals (but see Clevenger and Waltho 1999, 2005) gallinaceous birds (turkey,

pheasant, and grouse: for sage grouse see Lyon and Anderson 2003, Connelly et al. 2004), invertebrates (insects, spiders, worms) and for dispersing plants. Future options may be limited if the implications of roads on the survivorship of localized and low vagility species, e.g., marmots, bighorn sheep, and pikas, are not addressed. Gender responses to roads and crossing structures represent an unknown area of knowledge. These are only some of the many issues that need to be addressed.

Another area of importance addresses the impacts of the noise of roadways, and how it affects local and wide ranging species, such as bears and neotropical migrants. Provocative work suggests that noise as indexed by volume and frequency has important negative effects on decreasing the bird species richness and diversity (Rheindt 2003). We have added a research component that addresses the road noise issue to our small mammal research for this project.

Priority

Continue research that addresses the reactions and adaptations of wildlife to roads and wildlife crossing structures. Research that examines the assemblages of species reactions to roads and crossing structures would be the most productive in relation to creating effective mitigation measures that allow the full range of wildlife species to move across and underneath transportation corridors. Understanding the variables that contribute to wildlife behavioral reactions and how they may change over time is important. If we strive to create effective crossing structures that wildlife adapt to and actually use, we must consider extending monitoring efforts of crossing structures over several years in order to document the range of habituation and adaptation periods. These will be different among species and places. This priority can be addressed through specific regional wildlife-road research and also species-specific studies that may be broadened to include these objectives. Within each region of the country the local scientists and wildlife and land managers are the professionals who can best address these questions, because wildlife reactions to roads and crossing structures vary from place to place. We know that a crossing structure type that works for one population in a specific place may need to be modified to work effectively with another population and place. Regional research that addresses the effects of roads, and their associated development, traffic, and noise on assemblages of species and those species reactions to mitigation measures would greatly contribute to creating effective mitigation measures that allow associated wildlife communities continued movement.

The effects of roads and crossing structures on ecosystem relationships is largely unknown and needs to be better assessed and understood.

Road effects on ecosystems and landscapes need to be studied and quantified. Wildlife crossing mitigation measures also need to be studied to assess their impact on ecosystems. Landscapes and ecosystems are affected by roads and other transportation structures synergistically with other human infrastructure, changed ecosystem processes, and changed wildlife and plant populations. The most obvious change to ecosystems is fragmentation. Fragmentation is a more difficult phenomenon to evaluate than direct effects on specific species, and must be analyzed over larger areas and greater time scales than most ecological studies. Forman et al. (1997, 2003) suggest using road density as a

measure of fragmentation caused by roads. Road density is a simple spatial measure, providing an overview of the landscape (Forman et al. 2003). Other types of fragmentation measures could also be used to evaluate roaded landscapes.

Further evaluation is also needed to understand how roads and mitigation measures influence and alter natural processes such as the flow of water, ecosystem dynamics (for example, the relationships between ungulates and their habitats), species interactions (for example, predator-prey dynamics, see Little et al. 2002), population movement (for example movement to breeding areas), and individual behavior (for example, the avoidance of roads by mothers with young, for grizzly bear see Proctor 2002). Ecological effects are often indirect, multi-causal, and cannot be measured as easily as counting road kill carcasses. This is in part the reason why relatively little is known about the effects of roads on ecosystem processes. Clearly, there is a need for a comprehensive synthesis that documents the indirect effects of roads on ecosystems and how these cumulative effects may in turn influence landscape permeability.

Priority

Understand the effects of road density on the landscape for species of concern and ecosystems in general. For many species, roads generally reduce population sizes and increase the risk of population extinction. However, most species populations can persist in the presence of at least some roads. Therefore, in the context of road impacts on wildlife, probably the most important and most difficult question to answer is: what is the critical density of roads in an area below which a population of interest can not persist? This question is not easy to answer because of the spatial and temporal complexities of road impacts. As road density increases, wildlife habitat becomes increasingly fragmented (Jaeger 2000). The numerical responses of large mammals to roads are generally interpreted as responses to a road density threshold. Road densities above the threshold significantly reduce the probability for sustainable populations and coexistence. Several models have been developed to predict wolf pack occurrence or survival in relation to road density in Minnesota and Wisconsin (Thiel 1985, Mech et al. 1988, Mladenoff et al. 1995, 1999). A road density threshold of 0.45 km/km^2 was identified that best classified pack and non-pack areas for wolves (Mladenoff et al. 1995). Similar road density thresholds were reported for pumas and brown bears (Van Dyke et al. 1986, Clevenger et al. 1997). However, these studies only scratch the surface of the problem of estimating critical road density. This is an area in which research is urgently needed. Other ecosystem components affected by roads could also be measured with road density, including peak flows in mountain streams (Foreman et al 2003), erosion, and the spread of invasive plants and the subsequent impacts for ecosystem integrity, to name a few.

Road density is a simple measure, but road impacts on ecosystems vary considerably with traffic volume, speed, and infrastructure width, surface, and design (Iuell et al. 2003). For example Foreman and et al. (2002) found grassland birds avoided regular breeding in patch edges near roads in direct proportion to road volume, moving breeding activities farther away (up to 1 kilometer away) from roads with greater vehicle numbers per day. In order to gain a more thorough understanding of such road effects, we suggest examining the properties of the roads in conjunction with density to ascertain the ecological relevance of each road.[115]

Other aspects of the roaded landscape could be analyzed for impacts to ecosystem function. Analyzing the specific form or spatial pattern of the network of remaining natural patches and roads could reveal ecosystem properties (Foreman et al. 2003). This could be accomplished in part through the use of indices of patch size or mesh size (Jaeger 2000). Different mesh/patch sizes of natural areas contribute to different ecological conditions (Forman et al. 2003). With such indices, studies could be compared and contrasted to evaluate how roads are affecting ecosystem function and the basic ecological processes such as water flow, disturbance regimes, predator-prey interactions, seed dispersal, and movement among populations. These effects could be summed over ecosystems to find the cumulative costs of roads over regions.

Priority

Measure the effects of wildlife mitigation measures on ecosystem dynamics. These assessments could be performed by monitoring specifically chosen ecological indicators at different levels of biological organization: genes, individuals, populations, and species across landscapes. Assessments would be performed both before and after placement in order to judge the effectiveness of our actions at connecting communities and populations and possible cumulative effects.[58] Ecosystem assessments using specific ecological indicators would benefit from standardization and accuracy testing in order to obtain a tangible conservation value of the studied crossing structure. That would allow assessment of the ecological value of mitigation measures and possible cost-benefit values of potential crossing structures. Examples of questions to be answered include but are not limited to: How does the wildlife crossing structure affect the predator-prey dynamics within an ecosystem? Does the presence of artificially increased vegetative cover near passages change the use of these areas by cover-associated species? How does placement of a crossing structure influence the willingness of target species to use it? For instance, if a structure is placed along a riparian area does it promote the passage of some species and individuals while hampering the movements of others? The accomplishment of the priorities in this task will take the concerted effort of many scientists.

The larger-scale landscape context of road effects and transportation programs needs to be addressed through connectivity analyses at the state/provincial and regional levels.

There is a need for all states and provinces to conduct state/providence wide connectivity analyses to help determine 'fracture zones' among conservation areas that can then be prioritized in transportation programs for mitigation efforts. These fracture zones are where transportation corridors bisect natural wildlife movement corridors and potentially restrict movement and permeability of the natural world. There appear to be few large-scale state- or province-wide landscape approach efforts to address the effects of the roaded landscape on wildlife and ecosystems. Although the concept of 'context sensitive planning' is gaining national attention within the transportation community, it does not appear to us to explicitly include the surrounding wildlife habitat. We believe connectivity analyses create a window of opportunity to include ecosystem level and landscape-scale considerations in transportation programs and individual projects.

Without a proactive approach, future measures aimed at patchwork retrofitting and restoration may remain a poor second choice to properly planned and maintained landscape permeability in most regions.

Currently, landscape-scale connectivity analyses have been conducted in a variety of formats in approximately 15 states and provinces. These include California,[187] Washington,[212] Montana,[205] Colorado, Utah, Arizona, New Mexico, and the eight southeastern states.[46] These analyses involved landscape linkage models and the creation of GIS generated maps, or workshops aimed at addressing statewide connectivity, or rapid assessment workshops centered on specific roads, where professionals from across the state met to identify and map all potential major landscape linkages within the state and the roadways that potentially fracture these connections. Similar efforts should to be conducted for all states and provinces and the results incorporated into spatially explicit statewide databases and programs so these maps and accompanying data can be used in DOT and MoT planning for linking mitigation and implementing changes in their long range programs.[80]

Priority

Researchers, agency personnel, non-profit organizations, and the public must come together to create and disseminate state and provincial wide connectivity analyses. We suggest collaboration in conducting the science, widely-attended workshops to enhance needed information exchange, and partnerships to fund these efforts. A likely partnership for connectivity analyses funding could include states DOTs and provincial MoTs and their wildlife agency counterparts who can benefit greatly from such analyses. This type of effort has worked in several states. Regional approaches may work best. An effective type of analysis might include GIS models that analyze landscape linkages based on four important variables: focal species movement patterns, land cover, human density, and road density,[212] or a more inclusive list of environmental variables.[215] Digital topographic data can also help identify movement corridors in places containing drainages and ridgelines. Finally, the collective knowledge of land managers, wildlife biologists, non-profit environmental organizations, and state DOT/provincial MoT professionals can be brought together in critical connectivity workshops where the participants can work synergistically to identify key landscape linkages and the transportation corridors that fragment them, and prioritize projects needed to restore wildlife and ecosystem permeability. In light of the amount of progress that has been made in these workshops in the past two years,[69,204,203,205] this priority holds great promise.

A continent-wide set of guidelines is needed for defining specifics in the consideration, placement, design, maintenance, and monitoring of crossing structures and other mitigation measures.

There is a need for research to aid in the development of guidelines to facilitate the planning, placement, design, maintenance, and monitoring of wildlife crossing structures across North America. Transportation planners, engineers, and biologists need tools to effectively mitigate for the effects of roads on all wildlife species within affected

communities. Although wildlife crossing structures have been built for more than three decades, there is no standardized set of guidelines to assist these professionals and other agency personnel to mitigate for terrestrial and aquatic wildlife.[11] A North American set of guidelines for wildlife crossing structures would include specifics on conditions that trigger the consideration of mitigation measures, how and when to plan for structures, where to locate mitigation measures, design considerations, how to combine several types of efforts such as fences, underpasses, and ROW escape structures, standards for monitoring and maintaining structures, and how to measure the success of projects.

Priority

Define the necessary conditions for considering when to identify areas in need of wildlife crossing mitigation measures. Predictive models or threshold requirements would help determine when (a) crossing structure(s) is/are needed to help mitigate for certain volumes of traffic, safety considerations, road kill hotspots, the presence of endangered, threatened species or species of special concern, landscape linkages fracture zones created by transportation corridors, and the presence and need for movement of surrounding wildlife populations throughout critical habitat.

Priority

Engage the research community in the development of guidelines for the placement of crossing structures. Scientists and wildlife managers and biologists need to critically review the habitat-based linkage or movement models and rapid assessment techniques currently used to identify passage placement, and identify a suite of possible methods for practitioners. Emphasis should be on criteria to locate mitigation measures.[111]

Priority

Design considerations need to be adequately addressed for the full suite of crossing structures. There is a need for research to help in the selection of target species, and the determination of the number, size, and dimensional characteristics of structures needed within an area to help maintain maximum permeability for the suite of associated species.[80] Design guidelines for mitigation measures associated with crossing structures are also needed. Considerations include determining the required lengths of fences erected to guide wildlife (both large and small) to crossing structures, addressing the suitability of establishing or eliminating median islands in conjunction with crossing areas, creating underpasses with a naturally lit open space in the median of divided highways-in effect creating two underpasses under travel lanes rather than one long darker underpass, taking into account other nearby transportation corridors such as railways, retrofitting existing culverts for fish and other aquatic species, and possible alternatives or complements to crossing structures such as remotely sensed active lighted warning signs, possible crosswalks over low volume roads, the clearing of vegetation, temporary closure of roads, public transit options, reduced speed zones, and the elimination of certain roads (road decommission). Indeed several measures may be coupled for maximum effectiveness.

Priority

   Monitoring standards for crossing structures need to be researched and created. Bank et al.[11] suggest a national U.S. policy requiring post construction monitoring and maintenance measures for wildlife. Most existing structures have seldom if ever been monitored, or have been only sporadically checked to determine if they have served their purpose[111]. Guidance on monitoring efforts and temporal specifications would greatly assist managers, planners, and biologists and allow for comparable analyses among structures to ascertain their efficacy. The majority of past and current monitoring projects have been conducted in concert with academic institutions and the U.S. Fish and Wildlife Service. This monitoring, if done correctly, is essentially research. Future monitoring research could be standardized, implemented by, and mandated for future projects by the state wildlife and transportation agencies and federal agencies, including resource based agencies such as the U.S. Fish and Wildlife Service, Environment Canada, Fisheries and Oceans Canada, and transportation entities, for example the Federal Highway Administration and Transport Canada. The overall standardization of monitoring projects would mean a commitment of necessary funds from U.S. Federal Highways Program and other sources. The expected benefit would be an enhanced understanding of which structures work most effectively in specific situations.

Priority

   North American guidelines for crossing structures need to include methods for defining success and effectiveness[11]. Defining success would involve addressing the number of individuals (including the difference between males and females and juveniles and adults) of a target species who have used a structure, number of species found to use a structure, use by endangered and other high needs species, reduction of wildlife-vehicle-crashes, as well as other measures. Fish passages created in retrofitted and replaced culverts and bridges along streams have been evaluated through a quantifiable checklist of goals accomplished: e.g. the number of a certain species using the new passage, the number of kilometers those species have traveled upstream, how many individuals breed and re-populate a specified river distance within a watershed. These kinds of quantifiable measures present an objective method for assessing wildlife-landscape permeability across roadways and would greatly improve the credibility of wildlife crossings science and practice.

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Appendix B: Application of SPFS in Other States or Time Periods

As previously stated, applying a safety performance function (SPF) in another state, or application in the same state for different years, requires the model to be recalibrated to reflect differences across time and space in factors such as collision reporting practices, weather, driver demographics, and wildlife movements.

Since the SPFs developed for this report used state-wide data, they should also be recalibrated where they are being applied to a specific subset of the roadway system. As an example, wildlife crossings will be installed in locations with significant wildlife populations, a history of animal–vehicle collisions, and other site characteristics which make crossings favorable, and which are not common on the entire road system. When an evaluation study of crossing effectiveness is undertaken, the areas with crossings should be compared to areas without crossings, but which are as similar as possible to the treated segments. The SPFs should be recalibrated using these untreated segments as a reference group.

In the recalibration procedure, a multiplier is estimated to reflect these differences by first using the models to predict the number of collisions for a sample of sites for the new state or time period. The sum of the collisions for those sites is divided by the sum of the model predictions to derive the multiplier.

Step 1 – Assemble Data:
Assemble data and crash prediction models for the road segments of interest. For the time period of interest, obtain the count of animal–vehicle collisions and obtain or estimate the average AADT.

Step 2 – Estimate Recalibration Multiplier:
Apply the SPF to all sites. The sum of the observed collisions for those sites is divided by the sum of the SPF predictions to derive the multiplier.

Step 3 – Recalibrate Dispersion parameter, k:

a) For each segment, apply the recalibrated SPF from Step 2 to estimate the expected crash frequency, m, for each segment
b) A linear regression model is fit to the data as follows, where x is the collision frequency at a site:

Model: $y = a + k*z$

where,
$y = (m-x)^2 - m$
independent variable $z = m^2$
a is an intercept term
k is the slope of the line and is equal to the dispersion parameter

This model can be fit with many statistical or spreadsheet software packages. Alternatively, one can fit the model using the sample data and relatively simple equations as follows:

Each segment, i, is an observation of (z_i, y_i): i=1,...,n.

  i)   Calculate the sample mean of the variables y and z, $\bar{y}$ and $\bar{z}$
  ii)   Estimate the parameters a and k using the following formulae

$$k = \frac{\sum (z_i - \bar{z})(y_i - \bar{y})}{\sum (z_i - \bar{z})^2}$$

Worked Example

As an example, consider that it is desired to recalibrate the California model CA1 for use in Utah for the time period 1996-2000.

Step 1
The SPF to be applied is: total animal–vehicle crashes/mile-yr
$$= \exp(-7.8290)(AADT)^{0.6123}$$

The length, crash and AADT data for all 3,699 rural two-lane roadway segments in Utah is assembled. For each site the total number of animal–vehicle collisions from 1996 to 2000 is summed and the average AADT for the same time period calculated.

Step 2
The SPF is applied to all sites and the observed collisions and predictions are summed.

sum of the observed collisions = 5,086
sum of SPF predictions = 933

The recalibration multiplier is calculated:

Multiplier = 5,086/933 = 5.45

The multiplier is very large implying that the animal–vehicle collision frequency is much higher in Utah during 1996-2000 than in California during the time period the SPF was calibrated for (1991-2002).

The recalibrated SPF is: total animal–vehicle crashes/mile-yr
$$= 5.45 * \exp(-7.8290)(AADT)^{0.6123}$$

Step 3
The following calculations are performed for each segment:

$y = (m-x)^2-m$
$z = m^2$

The average values are found to be:

$\bar{y} = 16.36$

$\bar{z} = 0.20$

$$k = \frac{\sum(z_i - \bar{z})(y_i - \bar{y})}{\sum(z_i - \bar{z})^2}$$

$$k = \frac{174244}{98193} = 1.775$$

A2: Goodness of fit (GOF) tests for assessing which SPF to adopt
Adapted from: Washington S., Persaud B., Lyon C., and Oh J. Validation of Accident Models for Intersections. Federal Highway Administration, Report FHWA-RD-03-037, Washington, D.C., 2005.[240]

Several GOF measures can be used to assess model performance. It is important to note at the outset that only after an assessment of many GOF criteria is made, can the performance of a particular model or set of models be assessed. In addition, a model must be internally plausible, and agree with known theory about crash causation and processes. The GOF measures used were:

Pearson's Product Moment Correlation Coefficients Between Observed and Predicted Crash Frequencies
Pearson's product moment correlation coefficient, usually denoted by *r*, is a measure of the linear association between the two variables Y_1 and Y_2 that have been measured on interval or ratio scales. A different correlation coefficient is needed when one or more variable is ordinal. Pearson's product moment correlation coefficient is given as:

$$r = \frac{\sum(Y_{i1} - \overline{Y}_1)(Y_{i2} - \overline{Y}_2)}{\left[\sum(Y_{i1} - Y_1)^2 \sum(Y_{i2} - Y_2)^2\right]^{1/2}}$$

where
$\overline{Y}$ = the mean of the Y_i observations.

A model that predicts observed data perfectly will produce a straight line plot between observed (Y_1) and predicted values (Y_2), and will result in a correlation coefficient of exactly 1. Conversely, a linear correlation coefficient of 0 suggests a complete lack of a linear association between observed and predicted variables. The expectation during model validation is a high correlation coefficient. A low coefficient suggests that the

model is not performing well and that variables influential in the calibration data are not as influential in the validation data. Random sampling error, which is expected, will not reduce the correlation coefficient significantly.

Mean Prediction Bias (MPB)
The MPB is the sum of predicted accident frequencies minus observed accident frequencies in the validation data set, divided by the number of validation data points. This statistic provides a measure of the magnitude and direction of the average model bias as compared to validation data. The smaller the average prediction bias, the better the model is at predicting observed data. The MPB can be positive or negative, and is given by:

$$MPB = \frac{\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)}{n}$$

where

n = validation data sample size; and

$\hat{Y}$ = the fitted value Y_i observation.

A positive MPB suggests that on average the model overpredicts the observed validation data. Conversely, a negative value suggests systematic underprediction. The magnitude of MPB provides the magnitude of the average bias.

Mean Absolute Deviation (MAD)
MAD is the sum of the absolute value of predicted validation observations minus observed validation observations, divided by the number of validation observations. It differs from MPB in that positive and negative prediction errors will not cancel each other out. Unlike MPB, MAD can only be positive.

$$MAD = \frac{\sum_{i=1}^{n}\left|\hat{Y}_i - Y_i\right|}{n}$$

where
n = validation data sample size.

The MAD gives a measure of the average magnitude of variability of prediction. Smaller values are preferred to larger values.

Mean Squared Prediction Error (MSPE) and Mean Squared Error (MSE)
MSPE is the sum of squared differences between observed and predicted crash frequencies, divided by sample size. MSPE is typically used to assess error associated with a validation or external data set. MSE is the sum of squared differences between

observed and predicted crash frequencies, divided by the sample size minus the number of model parameters. MSE is typically a measure of model error associated with the calibration or estimation data, and so degrees of freedom are lost (p) as a result of producing Y_{hat}, the predicted response.

$$\text{MSE} = \frac{\sum\limits_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n_1 - p}$$

$$\text{MPSE} = \frac{\sum\limits_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n_2}$$

where
n_1 = estimation data sample size; and
n_2 = validation data sample size.

A comparison of MSPE and MSE reveals potential overfitting or underfitting of the models to the estimation data. An MSPE that is higher than MSE may indicate that the models may have been overfit to the estimation data, and that some of the observed relationships may have been spurious instead of real. This finding could also indicate that important variables were omitted from the model or the model was misspecified. Finally, data inconsistencies could cause a relatively high value of MSPE. Values of MSPE and MSE that are similar in magnitude indicate that validation data fit the model similar to the estimation data and that deterministic and stochastic components are stable across the comparison being made. Typically this is the desired result.

Appendix C: Theoretical Background of Network Screening for Proportion Method

This method was first proposed by Heydecker and Wu.[119] In this method, the proportion of collision type (p_i) at a site i with total crashes of n_i and target crash x_i is assumed to follow the binomial distribution.

$$f(x_i / n_i, \mu) = \binom{n}{x_i} \mu_i^{x_i} (1 - \mu_i)^{n_i - x_i}, 0 \le x_i \le n_i \qquad (C1)$$

where $\binom{n}{x}$ is a binomial coefficient defined by

$$\binom{n}{x} = \frac{n!}{x!(n-x)!} \qquad (C2)$$

The expected proportion at a site, μ_i, is constant for a given site and varies randomly from site to site. Heydecker and Wu[119] assumed that μ_i to follow Beta distribution, which is defined as

$$g(\mu / \alpha, \beta) = \frac{\mu^{\alpha-1}(1-\mu)^{\beta-1}}{B(\alpha, \beta)}, \quad 0 < \mu < 1 \qquad (C3)$$

where

$$B(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha + \beta)}) \qquad (C4)$$

where α and β are the parameters of Beta prior distribution and $\Gamma(.)$ defined as

$$\Gamma(z) = \int_0^\infty e^{-t} t^{z-1} dt \qquad (C5)$$

Also the mean of Beta distribution is given by

$$E(\mu) = \frac{\alpha}{\alpha + \beta} \qquad (C6)$$

where $E(\mu)$ is the prior estimate of μ_i.

Variance of beta distribution is given by

$$Var(\mu) = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)} \qquad (C7)$$

Combining Binomial distribution (C1) and Beta distribution (C4) results into unconditional Binomial-Beta distribution, which can be written as follows

$$h(x_i / n_i, \alpha, \beta) = \binom{n_i}{x_i} \frac{B(\alpha + x_i, \beta + n_i - x_i)}{B(\alpha, \beta)} \qquad (C8)$$

Using Bayes theorem to combine the prior Beta distribution with site specific collision data (n_i, x_i) for each site to derive the adjusted posterior beta distribution which can be written as

$$g(\mu_i / \alpha', \beta') = \frac{\mu^{\alpha'-1}(1 - \mu)\beta' - 1}{B(\alpha', \beta')} \qquad 0 < \mu < 1 \qquad (C9)$$

α' and β' are posterior parameters and can be defined as

$$\alpha' = \alpha + x_i \qquad (C11)$$

$$\beta' = \beta + n_i - x_i \qquad (C12)$$

Equation (C9) is also a Beta Distribution

For the posterior distribution, the expected value for each site, i, is given by the following equation.

$$E(\mu_i) = \frac{\alpha'}{\alpha' + \beta'} \qquad (C13)$$

Likewise, the posterior variance is given by

$$Var(\mu_i) = \frac{\alpha'\beta'}{(\alpha' + \beta')^2(\alpha' + \beta' + 1)} \qquad (C14)$$

A limiting value of proportion is predefined say, p*, for a given site and collision type. The pattern score is defined as the probability that the expected value of μ_i is greater than p*. Sites are ranked in descending order of this probability. If the limiting proportion was selected as the median, μ_m the pattern score can be expressed as:

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$$P(\mu_i > \mu_m) = 1 - B(\mu_m, \alpha', \beta')$$
<div align="right">(C15)</div>

Parameter Estimation of Beta Prior Distribution

The parameters α and β of the Beta distribution can be expressed in terms of moments (mean and variance) as shown in equations (C16) and (C17). The mean and variance from the observed data are used to estimate α and β.

To illustrate, suppose there are 1, 2, 3, ………i, ……m sites under consideration. μ_i is the proportion of a specific collision type for site i, that is $\mu_i = x_{ij} / n_i$. where x_{ij} is the total numbers of target collisions of type, j, during the study period at site i and n_i is the total number of all types of collisions at site i during the same period. The mean proportion of target collisions, j, is given by

$$\overline{\mu}_j = \frac{\sum\limits_{i=1}^{m} \mu_{ij}}{m}$$
<div align="right">(C16)</div>

where $\overline{\mu}_j$ is the mean proportion of target collision type j.

Similarly, the variance is given by

$$s^2 = \frac{1}{m-1}\left[\sum\limits_{i=1}^{m}\left(\frac{x_i^2 - x_i}{n_i^2 - n_i}\right) - \frac{1}{m}\left(\sum\limits_{i=1}^{m}\frac{x_i}{n_i}\right)^2\right], \quad n \geq 2$$
<div align="right">(C17)</div>

For a sufficiently large sample, the sample mean, $\overline{\mu}_j$, represents the expected value, $E(\mu_j)$ and the sample variance, s^2, represents the population variance, $Var(\mu)$. The variance can also be expressed as

$$s^2 = \frac{\dfrac{\alpha^2}{\overline{\mu}} - \alpha^2}{\left(\dfrac{\alpha}{\overline{\mu}}\right)^2\left(\dfrac{\alpha}{\overline{\mu}} + 1\right)}$$
<div align="right">(C18)</div>

This can be further simplified as

$$s^2 = \frac{\dfrac{1}{\bar{\mu}} - 1}{\left(\dfrac{1}{\bar{\mu}}\right)^2 \left(\dfrac{\alpha}{\bar{\mu}} + 1\right)}$$ $(C19)$

This gives

$$\alpha = \frac{\bar{\mu}^2 - \bar{\mu}^3 - s^2\bar{\mu}}{s^2}$$ $(C20)$

Then β can be estimated as

$$\beta = \frac{\alpha}{\bar{\mu}} - \alpha$$ $(C21)$

Posterior Beta Distribution and Pattern Score

The median, μ_m, of beta prior distribution is such that

$$\int_{\eta_m}^{1} g(\mu)/\alpha, \beta)d\mu = 0.5$$ $(C22)$

Once α and β are estimated, μ_m can be estimated using an Excel worksheet function. The posterior parameters, α' and β', can be calculated by using equations (C11) and (C12). The pattern score can be calculated using equation (C15).

To summarize the above discussion, following is a stepwise procedure to estimate the parameters of to estimate the parameters of beta prior and beta posterior distributions, there by the pattern score.

1. Divide the sites into logical groups. For example, two-lane rural roads analyzed separately from multilane roads.
2. Identify the different types of crashes.
3. Find total number of crashes of each type during the study period in each site, x_i.
4. Find total number of all types of crashes in each site, n_i.
5. Calculate the proportion, x_i/n_i for each site and for each type of crash of interest.
6. Calculate the mean of the proportions for each crash type, $\bar{\mu}_j$
7. Calculate variance using equation (C17)
8. Calculate α and β using equations (C20) and (C21)
9. Estimate the median of Beta prior distribution using Excel function (μ_m = betainv(0.5, α, β).
10. Calculate parameters of posterior Beta distribution as $\alpha' = \alpha + x_i$ and $\beta' = \beta + n_i - x_i$
11. Estimate the pattern score using Excel function as $P(\mu i > \mu_m) = 1$-betadist (μ_m, α', β').

Appendix D: Illustrating Regression to the Mean

Consider the data in Table 44, which pertains to crash counts at 3,699 one-mile road segments in Utah. These segments averaged 0.281 crashes per year during 1995-1997 and 0.279 crashes per year in 1998-2000, further evidence that they were largely unaltered during the six year period from 1995 to 2000, according to information in the Highway Safety Information System (HSIS)[108] from which these data were extracted. In Table D-1, sections are grouped into rows based on the count of crashes in 1995-97, shown in Column 1. As the last column shows, those sections in groups which in 1995-97 had more than the average number of crashes in this period (0.281 crashes per year of 0.843 crashes in 3 years) experienced a reduction in crashes in 1998-2000. Sections with fewer crashes than the average (i.e., those with zero) experienced a considerable increase.

These changes are due to random fluctuations in short term counts that result in a phenomenon known as regression to the mean. The result is that such changes can be erroneously attributed to a countermeasure in an observational study that simply compares crashes before and after implementation. In particular, if the segments with high counts are selected for treatment (as often happens) the positive effects of the treatment in such a naïve study would be exaggerated by the amounts shown in the last column of the earlier rows in the table. This random fluctuation also suggests that a site with a higher collision count is not necessarily a stronger candidate for safety improvement than a site with a lower count. The upshot of this phenomenon is that the crash count by itself is not good enough for estimating the safety of a site for use in identifying candidate improvement locations and in estimating the safety effect of potential or implemented countermeasures. This is why more sophisticated predictive tools are needed. Evidence of regression to the mean in two other States' data used for this study is presented in Tables 45 and 46.

Table 44: Wildlife-vehicle colllision data for Utah illustrating regression to the mean

Crashes 3 yrs Prior	Number of Sites	Crashes 1995-1997	Crashes 1998-2000	% difference
≥17	17	416	340	-18.3
16	6	96	86	-10.4
15	8	120	97	-19.2
14	6	84	73	-13.1
13	5	65	45	-30.8
12	5	60	57	-5.0
11	11	121	101	-16.5
10	12	120	119	-0.8
9	17	153	112	-26.8
8	14	112	99	-11.6
7	19	133	108	-18.8
6	34	204	194	-4.9
5	34	170	160	-5.9
4	51	204	175	-14.2
3	93	279	250	-10.4
2	173	346	282	-18.5
1	431	431	377	-12.5
0	2763	0	431	infinite increase

Table 45: Data for North Carolina illustrating regression to the mean

Crashes 3 yrs Prior	Number of Sites	Crashes 1996-1998	Crashes 1999-2001	% difference
≥32	6	242	227	-6.2
31	3	93	65	-30.1
30	3	90	70	-22.2
29	3	87	29	-66.7
28	1	28	23	-17.9
27	2	54	50	-7.4
26	1	26	19	-26.9
25	5	125	115	-8.0
24	5	120	91	-24.2
23	3	69	43	-37.7
22	1	22	20	-9.1
21	10	210	174	-17.1
20	3	60	37	-38.3
19	7	133	103	-22.6
18	8	144	105	-27.1
17	4	68	45	-33.8
16	7	112	89	-20.5
15	19	285	213	-25.3
14	28	392	303	-22.7
13	39	507	450	-11.2
12	33	396	338	-14.6
11	44	484	386	-20.2
10	55	550	404	-26.5
9	94	846	746	-11.8
8	114	912	654	-28.3
7	144	1008	779	-22.7
6	216	1296	1145	-11.7
5	290	1450	1179	-18.7
4	429	1716	1321	-23.0
3	653	1959	1728	-11.8
2	1167	2334	2066	-11.5
1	2518	2518	2482	-1.4
0	13125	0	2586	Infinite increase

Table 46: Data for California illustrating regression to the mean

Crashes 3 yrs Prior	Number of Sites	Crashes 997-1999	Crashes 2000-2002	% difference
≥6	8	61	41	-32.8
5	8	40	27	-32.5
4	21	84	41	-51.2
3	55	165	84	-49.1
2	147	294	149	-49.3
1	792	792	343	-56.7
0	11941	0	951	infinite increase

Appendix E: Hotspot Identification of Wildlife-Vehicle Collisions:

FIELD STUDIES & SPATIAL ANALYSES

A LITERATURE REVIEW

Lead: Dr. Anthony P. Clevenger, Amanda Hardy, Kari Gunson

CONTENTS

The literature description for this appendix contains stand-alone references. The literature review of all other appendices is contained in the body of the literature citation.

I. WILDIFE-VEHICLE COLLISION ANALYSIS

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Bashore, T.L., Tzilkowski, W.M., and E.D. Bellis. 1985. Analysis of deer-vehicle collision sites in Pennsylvania. Journal of Wildlife Management 49(3): 769-774.

Bellis, E.D., Graves, H.B. 1971. Deer mortality on a Pennsylvania interstate highway. Journal of Wildlife Management. 35(2):232-237.

Biggs, J., Sherwood, S., Michalak, S., Hansen, L., Bare, C. 2004. Animal-related vehicle accidents at the Los Alamos National Laboratory, New Mexico. The Southwestern Naturalist. 49(3):384-394.

Caryl, F.M. 2003. Ungulate mortality on a forested highway. University of East Anglia, Norwich. M.Sc. thesis. 42 pp.

Finder, R.A., Roseberry, J.L., and A. Woolf. 1999. Site and landscape conditions at white-tailed deer/vehicle collision locations in Illinois. Landscape and Urban Planning 44: 77-85.

Gundersen, H. and H.P. Andreassen. 1998. The risk of moose-collision: a logistic model for moose-train accidents. Wildlife Biology 4(2): 103-110.

Gundersen, H., Andreassen, H.P., Storaas, T. 1998. Spatial and temporal correlates to Norwegian train-moose collisions. Alces 34: 385-394.

Hubbard, M.W., Danielson, B.J., and R.A. Schmitz. 2000. Factors influencing the location of deer-vehicle accidents in Iowa. Journal of Wildlife Management 64(3):707-713.

Joyce, T.L. and S.P. Mahoney. 2001. Spatial and temporal distributions of moose-vehicle collisions in Newfoundland. Wildlife Society Bulletin 29(1): 281-291.

Kassar, C., Bissonette, J.A. 2005. Deer-vehicle crash hotspots in Utah: data for effective mitigation. UTCFWRU Project Report No. 2005(1):1-28. Utah Cooperative Fish and Wildlife Research Unit, Utah State University, Logan Utah.

Malo, J.E., Suarez, F., and A. Diez. 2004. Can we mitigate wildlife-vehicle accidents using predictive models? Journal of Applied Ecology 41: 701-710.

Nielsen, C.K., Anderson, R.G., and M.D. Grund. 2003. Landscape influences on deer-vehicle accident areas in an urban environment. Journal of Wildlife Management 67(1): 46-51.

Nielsen, S.E., Herrero, S., Boyce, M.S., Mace, R.D., Benn, B., Gibeau, M.L., Jevons, S. 2004. Modelling the spatial distribution of human-caused grizzly bear mortalities in the Central Rockies ecosystem of Canada. Biological Conservation. 120:101-113

Premo, D.B.P., Rogers, E.I. 2001. Town of Amherst deer-vehicle accident management plan. White Water Associates, Inc., Amasa, Michigan (http://www.white-water-associates.com)

Rogers, E. 2004. An ecological landscape study of deer-vehicle collisions in Kent County, Michigan. Report for the Michigan State Police, Office of Highway Safety and Planning. White Water Associates, Inc., Amasa, MI 49903. 56 pp.

Romin, L.A. and J.A. Bissonette. 1996. Temporal and spatial distribution of highway mortality of mule deer on newly constructed roads at Jordanelle Reservoir, Utah. The Great Basin Naturalist 56(1): 1-11.

Seiler, A. 2005. Predicting locations of moose-vehicle collisions in Sweden. Journal of Applied Ecology 42: 371-382.

Simek, S.L., Jonker, S.A., Endries, Mark J. 2005. Evaluation of principal roadkill areas for Florida black bear. ICOET 2005.

Singleton, P.H., Lehmkuhl, J.F. 1999. Assessing wildlife habitat connectivity in the Interstate 90 Snoqualmie Pass Corridor, Washington. ICOWET III.

II. SPATIAL ANALYSIS TECHNIQUES

Boots., B.N. and A. Getis. 1988. Point Pattern Analysis. Sage Publications, Inc. Newbury Park, California. 85 pp.

Burka, J., D. Nulph, and A. Mudd. 1997. Technical approach to developing a spatial crime analysis system with ArcView GIS. INDUS Corporation and U.S. Department of Justice.

Lee, J. and D.W.S. Wong. 2001. Statistical Analysis with ArcView GIS. John Wiley and Sons, Inc., New York, New York. 192 pp.

Levine, N., K.E. Kim and L.H. Nitz. 1995. Spatial analysis of Honolulu motor vehicle crashes: I. Spatial Patterns. Accident Analysis and Prevention 27(5):663-674.

Levine, N. 1996. Spatial statistics and GIS: software tools to quantify spatial patterns. Journal of the American Planning Association 62(3): 381-391.

Levine, N 1999. Quickguide to CrimeStat. Ned Levine and Associates, Annandale, VA.

Levine, N. 2004. CrimeStat III: Distance analysis. Chapter 5 in: A spatial statistics program for the analysis of crime incident locations. Ned Levine & Associates: Houston, Texas, and the National Institute of Justice, Washington, D.C., USA.

Spooner, P.G., I.D. Lunt, A. Okabe and S. Shiode. 2004. Spatial analysis of roadside *Acacia* populations on a road network using the network K-function. Landscape Ecology 19:491-499.

I. WILDLIFE-VEHICLE COLLISION ANALYSIS

Allen, R.E., McCullough, D.R. 1976. Deer-car accidents in southern Michigan. Journal of Wildlife Management 40(2): 317-321.

Objective: to identify the time, place, and characteristics of traffic and deer that contributes to collisions. It was hoped that such an understanding would suggest measures to reduce collisions

Data layers: 10 counties in S. Michigan; data on DVC from accident reports, 1966-1967
- variables analyzed for all accidents: date, day of week, time, speed of car, sex of deer, road type
- added to 1967 data: location within 0.16 km from a landmark; number deer seen at time of accident; fate of deer involved; whether car driven or towed away; extent of injuries
- traffic volume data from MI Dept of State Highways: average traffic volume for various time intervals (hourly, daily, monthly)

Analyses: 3 areas from highest accident roads chosen for habitat analysis: all accidents plotted on aerial photos and roadside habitat classified as cropland, forest, or unimproved field

Results: most accidents occurred between 1600-0200; 2 peaks, sunrise and 1-2 hours after sunset; traffic volume and DVC correlated for evening and nighttime hours (85% of variation in DVC accounted for by traffic volume)

- number of accidents and traffic volume highest on weekends; largest number of DVC in fall and early winter
- in 3 sections where habitat determined, accidents and habitat types occurred in similar proportions
- % of accidents increased up to a speed of 80-95 kph, then declined at higher speeds

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Bashore, T.L., Tzilkowski, W.M., and E.D. Bellis. 1985. Analysis of deer-vehicle collision sites in Pennsylvania. Journal of Wildlife Management 49(3): 769-774.

Objectives: examined road-kill locations plotted on highway maps by PA Game Protectors since 1968. A cursory exam revealed that deer kills tend to be aggregated at specific sites where accidents occur year after year. Analyzed aerial photos and highway and topo maps and conducted field studies to determine which factors characterize concentrations of collisions at particular sites. A model was developed to predict probabilities that a section of highway would be a high kill site and then tested for reliability.

4 PA counties studied, used 2-lane hard-top roads, 51 paired sites (kill and control), data collected from 1 July-30 Oct 1979 and 27 June-1 Oct 1980

Data layers: residences (number/ha); commercial buildings (number/ha); other buildings (number/ha); banks (prop. of terrain elevated more than 1m above road surface); gullies (more than 1m below road surface); level (not bank or gully); wooded; non-wooded; barren; distance to woodland; increasing slope; decreasing slope; no slope; angular visibility; in-line visibility; shortest visibility; speed limit; fencing; guard rails

Data obtained by selecting a random point from within each 100m interval of site length and running a 100m transect perpendicularly from each side of the road; at sites shorter than 100m, two points were randomly selected

Analysis: stepwise logistic regression used to test the importance of the variables used in the model; 5 pairs of sites randomly selected for a test of the model's predictive ability

Results: 9 of 19 variables selected for inclusion in model (residences, commercial buildings, other buildings, shortest visibility, in-line visibility, speed limit, distance to woodland, fencing, non-wooded area);
- 85% of kill locations had a prob. of 0.70 or greater of being classified as kill site; 89% of control had a prob. of 0.30 or less of being classified as kill site
- high correlation between speed limit and in-line visibility; between residences and other buildings; removal of correlated variables did not significant change model
- 9 and 7 variable models performed equally well in predicting kill and non-kill sites; 5 kill locations correctly classified, one control location misclassified by both models

Discussion: DVCs not random in time or space; kills aggregated

Bellis, E.D., Graves, H.B. 1971. Deer mortality on a Pennsylvania interstate highway. Journal of Wildlife Management. 35(2): 232-237.

Objective: to present the results of an analysis of data on highway mortality collected from November 1968 through December 1969

Data layers: data collected from an 8.03 mile section of I-80; divided into 212 contiguous sectors of 200-ft length

- kill data obtained from game protector who filled out researcher supplied data sheets (date, location by sector number, highway lane, sex, age class); it was understood that many kills were probably not reported
- 5 portions of each of the 212 sectors analyzed for physical and vegetation factors that might affect deer mortality: planted ROW on each side of highway; area adjacent to ROW on each side of highway; median strip
- factors used in the analyses: quality and amount of vegetation; topography; area of ROW; presence of fences or guardrails
- Deer counts obtained from May 68-May 69 by spotlighting from vehicle

Results: 286 reported DVC; 67.9% of sectors had at least one DVC (max of 9 in one sector); road-kills often concentrated in groups of contiguous sectors

- 70% of deer seen through spotlighting were grazing (conservative estimate); suggests presence and type of vegetation within sectors accounted for much of variation in numbers killed
- low correlation between DVC and all measured variables- demonstrated that with our technique we could not account for the variation in numbers of deer killed
- examined data in a less analytical manner by considering combos of sectors in relation to overall topography
  - high mortality: (1) where sections of road lay in troughs formed by elevated median strips with steep banks and steep inclines on ROW; (2) where troughs terminated by reductions in elevation of the median strips allowing deer to easily cross road; (3) both sides of highway and median strip had good grazing and relief relatively flat
  - low mortality: (1) area with low relief, abundant food on ROW and chain link fence; (2) ROW declines sharply to a stream or other lowland area, guardrails present
- high correlation between number killed per month and number seen per month

Biggs, J., Sherwood, S., Michalak, S., Hansen, L., Bare, C. 2004. Animal-related vehicle accidents at the Los Alamos National Laboratory, New Mexico. The Southwestern Naturalist. 49(3): 384-394.

Objectives: to 1) analyze wildlife-vehicle accident data with respect to time, season, location, and species for accidents occurring on LANL internal and perimeter roads

and 2) perform an analysis of site characteristics at accident locations identified as hotspots…

Data layers: ~68 km of primary rd included in study; majority of traffic volume in early morning and late afternoon; WVC data from 1990-1999

- Accident data: from NMDGF, LAPD and LANL security force reports (date, time, location, species, cost of damage, injuries to humans, injuries to animals); accident locations recorded into GIS (sometimes based on approximate description of site)
- Hotspot characterization data: vegetation characteristics (dominant tree, shrub, forbs and grass sp.), posted speed limit, road type (straight, curve, hill), present of lighting, amount of available light (high, mod, low, none), presence and length of guardrails, height of fencing, slope characteristics, motorist visibility distance

Analyses: **Cluster analysis** using GIS nearest-neighbor index approach used to determine whether accidents were distributed randomly; deer and elk examined separately

- **density analysis** using the 'simple' type calculation of the GIS program and a search radius of 100 m applied to identify accident hotspots
- accident site characterization analysis: 15 hotspots selected, with 15 paired control sites; 100 m transect centered on site placed parallel to road on either side, 6 15 m transects (at 25, 50, 75 m marks) placed perpendicular to 100m transects; hotspot characterization data recorded along 15 m transects
- statistical analyses: Chi^2 used to test for differences in accident counts between seasons
    - exact binomial tests: to determine if differences occurred between the numbers of accidents in different pairs of seasons; also if significant difference occurred among hourly counts of accidents; deer and elk analyzed separately
    - Poisson regression: if accident count in given year significant difference from other years; also to test if association between monthly accident counts and monthly snowfall amounts significant; deer and elk analyzed separately
    - Logistic regression: to model status of an area as a hotspot or control as a function of measured variables
    - Fisher's exact test: if diff in recoded variables between hotspots and controls were statistically significant
    - Univariate logistic regression: as first step to identify potential predictors for a larger model; potential predictor variables chosen if 1) absolute value of the Wald statistic >1, 2) lit search revealed potential importance, or 3) authors thought important

Results: seasonal peaks in DVC (fall) and E(lk)VC (winter, fall); most accidents in late afternoon and evening hours

- Cluster analysis: EVC and DVC did not occur randomly
- Density analysis: identified several areas with higher concentrations of accidents
- Accident site characteristics: when considered 1 at a time, no variable measured was a statistically significant predictor of hotspot or control status; variables

chosen as predictors in final model were ln(average number woody stems >2m in height), and maximum slope

Discussion: ambiguous relationship between accidents and snowfall might derive from our pooling of snowfall and accident data by month instead of using daily snowfall measurements and accident counts
- Poor results with utility of different variables could be result of small sample size
- Because of small sample size, placed a higher priority on finding a well-fitting model that made sense rather than on finding one that was statistically significant

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Caryl, F.M. 2003. Ungulate mortality on a forested highway. University of East Anglia, Norwich. Dissertation (copyrighted) 42 pp.

Objective: to produce a multi-species empirical model of ungulate road mortality using highly accurate spatial data from field and GIS based sources in Kootenay National Park, British Columbia, Canada. It would then be determined if the model could be reproduced using GIS based variables only, to provide a quick and effective management tool to focus mitigation efforts at high risk locations

Data layers: species included moose, mule deer, white-tailed deer, elk and bighorn sheep
- Ungulate mortality data: date, number, species, sex, age, location from GPS;
- Control site data: randomly selected non-kill sites along highway; ratio of control sites to kill sites larger than one desirable due to greater expected variation in control environmental attributes
- Field based environmental variables: distance to cover (> 1m tall and continuous), % cover forest; % cover shrub; % cover herb; % cover bare ground; roadside slope; verge slope; adjacent land slope; inline visibility; angular visibility
- GIS based variables (using ArcView): elevation; distance to hydrology; distance to human use; road sinuosity ratio; change in elevation; habitat importance for deer, moose and elk; barrier

Analysis: Spearman's rho correlations used to screen for multicollinearity, removed one highly correlated biophysical variable before model development; differences between seasons compared using Chi^2 tests
- Model development: logistic regression, stepwise selection process using log likelihood ratio tests and a prob. value of 0.05 for entry and removal of variables to the model; selection process then repeated using only GIS based variables; Chi^2 used as a goodness-of-fit test of model appropriateness; Wald stats to test the significance of independent variables; direction of predictor influence verified using Mann-Whitney U tests; odds ratios examined to assess contribution that a unit increase in predictor variable made to outcome probability
- Model validation: 5 control and 5 kill sites randomly chosen to validate model's predictive ability; 0.29 chosen as classification cut-off for predicted group memberships based number of kill sites vs control sites; predicted probabilities classified into 3 groups: low, moderate and high risk of kill

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Results: Kill sites highly aggregated; highly significant seasonal differences (high in summer); road kills positively associated with daily traffic volumes

- 3 of 17 environmental variables shown to be reliable predictors: distance to humans, elevation, distance to cover; all had negative coefficients; 67.3% kill sites, 64.3% control sites predicted correctly, giving overall success of 65.2%
- 2 of 9 GIS variables shown to be reliable predictors: distance to humans, elevation; both had negative coefficients; 61.5% kill sites, 65.1% control sites predicted correctly, giving overall success of 64%
- Model testing: 3 of 5 control sites, 4 of 5 kill sites (70% of sites) correctly classified using GIS model
- Probability surface with low moderate and high collision probability created using 2 GIS variables

Discussion: kill sites not located randomly in time or space; kill sites found at lower elevations than control sites and closer to human use areas; odds of a kill decreased by 96% with each additional 1000 m elevation above sea level if all other variables controlled; odds of a kill decreased by 40% with each additional 1km distance from human disturbance sites; probability surface showed a close agreement with observed road kill locations, would be useful tool for quick assessment of possible high risk locations

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Finder, R.A., Roseberry, J.L., and A. Woolf. 1999. Site and landscape conditions at white-tailed deer/vehicle collision locations in Illinois. Landscape and Urban Planning 44: 77-85.

Objective: to determine if high deer/vehicle accident locations could be predicted from remotely sensed land use/land cover patterns

Data layers: 98 counties in IL; 1989-1993; rd segments with high concentrations of DVAs on state marked routes; n=86 locations with ≥15 reported DVAs analyzed

- Plotted 'hotspot' road segments using TIGER data files and Map and Image Processing System GIS software; road segments adjusted to 1.3 km; random locations on same route of same length for control purposes
- Landcover classification (Landsat TM): crops, forest, grass, water, developed, orchards; topographic physical features from aerial photographs and topographic maps

Analyses: 0.8 km radius buffer zone around each road segment to quantify and compare landscape composition and pattern using FRAGSTATS

- Simple correlation used to investigate relations among variables; highly correlated eliminated
- t-tests to determine if variable means differed between hotspots and controls; those indices with |t| values ≥3.0 selected as predictor variables for logistic regression
- stepwise logistic regression model selection process to obtain a preliminary equation

- AIC to compare models
- Stepwise selection process repeated using only landscape indices, satellite imagery data only
- 5 paired sites used to test models' predictive abilities

Results: variables included in model 1: % distant woody cover, % adjacent gully; natural log of area of recreational land within buffer, natural log of width of corridors crossing road; of 10 samples to test model validity, 5 control and 4 hotspots correctly predicted

- Variables included in model 2: Simpson's diversity index; natural log of woods mean proximity index; of 10 samples to test model validity, 4 control and 2 hotspots correctly predicted

Discussion: study demonstrated that DVA site statistics and RS habitat and highway data can be used to predict DVA locations

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Gundersen, H. and H.P. Andreassen. 1998. The risk of moose-collision: a logistic model for moose-train accidents. Wildlife Biology 4(2): 103-110.

Objective: to use a logistic model to establish the most risky train departures for Rørosbanen railway which has the highest risk of moose-train collisions per km in Norway (Gundersen et al. 1998). In the model we have included speed of train, type of train, time of day and lunar phase, besides climatic covariables know to be correlated with moose-train collisions.

Data layers: success (1) or failure (0) of train hitting moose;
train departures; train route; train predictor variables (average speed, train type, time of day);
daily average temperature; snow depth; lunar phase;
data recorded from Dec-Mar 1990-1997

Analysis: a logistic model was applied incorporating the above variables;
the most parsimonious model chosen using AIC;
another model made containing only passenger trains running the whole distance
between 2 towns, snow depth, daily average temp, lunar phase, train speed, time of day left station;
used data from 1990-1996 to predict the number of train-killed moose for each train for the winter of 1996/1997

Results: most parsimonious model included route, time of day, lunar phase, snow depth, temp;
according to AIC, this model is indistinguishable from one including average train speed;
best model for the second analysis included all predictor variables.
Problems with morning train results in second analysis due to introduction of logging activity in Storholmen in 1996.
Second model gave good results for morning train after removing 6 collisions at Storholmen

Discussion: authors introduced a new approach to study game-vehicle accidents by focusing on factors that cause vehicles to collide with game rather than focusing on the factors that cause game to be close to traffic arteries.

Gundersen, H., Andreassen, H.P., Storaas, T. 1998. Spatial and temporal correlates to Norwegian train-moose collisions. Alces 34: 385-394.

Objectives: In this study we reveal how temporal variation, i.e. climatic factors and moose population density, and spatial variation, i.e. landscape pattern and changes in food availability, correlate with moose-train collisions along the railway in Norway which is most burdened by wildlife collisions.

Data layers: train kills (time, location to nearest 100m)
daily average temperature, snow depth
size of moose pop estimate by population model Cersim (based on observations by hunters in previous season)

Analysis: 2 categories of analysis - temporal factors (climatic and pop density) and spatial factors (landscape patterns and food availability)
- Temporal factors: compared the freq. distribution of days w/ certain weather conditions (expected) w/ the freq. distribution of collisions at the various weather conditions (observed) by a goodness of fit-test. GLMs used to correlate moose pop size and number of collisions
- Spatial factors (regional): analyzed correlation between landscape patterns and number of collisions per 1km segment
    - Landscape patterns: 1) topography - measured as the difference in height from the bottom of the valley to the highest point within 2.5 km to East and West of line and averaged; 2) distance to the nearest side valley – because assumed to channel moose migratory behavior;
    - tested and corrected for autocorrelation in 1-km segments
- Spatial factors (local): to explain spatial variation of collisions, compared number of collisions before and after changes in food availability due to logging activity in two areas
    - One area had increased food availability while the second had decreased food availability
    - Linear model including factors that significantly correlated to yearly variation in collisions (climatic factors and population density) used to obtain estimate of expected number of collisions before and after change in food availability; expected vs observed compared with goodness of fit-test

Results: Temporal effects: number of collisions associated with both temp and snow depth; combined temp and snow depth into variable (accidental period) which started when snow depth exceeded 30 cm and lasted until temp stabilized above 0 degrees C. Number of days in new variable explained 83% of yearly variation in number of moose collisions; GLM including both accidental period and pop density explained 88% of yearly variation

Spatial effects: significant negatively correlated between number of collisions and distance to nearest side valley; no association between number of collisions and topography; changes in food availability strongly associated to number of collisions

Discussion: moose usually killed in winter on days with lots of snow and low temps; influenced by migratory routes to lower elevations and availability of food; temporal variation due to climatic factors, spatial variation due to migratory routes and food availability.

Hubbard, M.W., Danielson, B.J., and R.A. Schmitz. 2000. Factors influencing the location of deer-vehicle accidents in Iowa. Journal of Wildlife Management 64(3):707-713.

Objective: to examine the influence of highway and landscape variables on the number of DVAs in Iowa

Data layers: number of DVAs, traffic and landcover data obtained for all milepost markers within the state (n=9,575)
- GIS maps of habitat (Landsat imagery, 1990-1992): collapsed habitat types into cropland, woody cover, grass, artificial, water and miscellaneous
- White-tailed deer harvest numbers for each county from IDNR; DVAs from 1990-97 for state's highways from IDOT; traffic volume estimates linked to all accident sites
- For each DVA included: distance to nearest town or city, distance to nearest city with pop $\geq$ 2,000, number of bridges, number of lanes of traffic
- Accident location often recorded to nearest 0.10 mile, but more than 33% recorded at milepost, therefore all locations collapsed to nearest milepost

Analysis: dependent variable-number of accidents in each 1.61 km segment from 1990-97
- Randomly selected sample sites (n=1,284); clipped 2.59 km^2 landscape section with sample site
- FRAGSTATS used to characterize landscape sections; linked to number of DVAs for segments
- DVAs separated into 2 categories (0-13, >14 hits/segment) based on natural break and sample size
- Logistic regression: to examine relationship of DVAs to traffic, highway characteristics, human pop centers, and landscape variables; stepwise selection procedure for variable inclusion during model development
- Factor classification tree (FCT) constructed to refine ability to select high DVC areas
  - o Robust relative to a more standard cluster and discrimination analysis that might be used (Emmons et al. 1999)
  - o Followed method described by Venables and Ripley (1994) to find the rooted subtree with a minimum AIC

- Evaluated performance of logistic regression model by applying to a randomly selected set of DVA sites not included in model development (n=245)

Results: 67% of 9,575 mileposts associated with DVA; >25% DVAs at 3.4% of mileposts (325)

- Significant 6-variable model produced; 4 variables landscape features, 2 highway characteristics
- FCT final classification produced a tree with 57 nodes and a misclassification rate of 0.153%; bridge frequency was best predictor of high DVA sites
- Model validation: correctly classified 63.3% of sites

Discussion: edges not found to be important, however it is possible that the resolution of our data was too coarse to identify all edges used by deer as travel corridors. Bridges always indicate points where major edge-creating landscape features intersect roadways, and therefore may be better predictors of concentrations of DVAs than more broadly defined edge indices

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Joyce, T.L. and S.P. Mahoney. 2001. Spatial and temporal distributions of moose-vehicle collisions in Newfoundland. Wildlife Society Bulletin 29(1): 281-291.

- OBJECTIVE: "we …relate rate & severity of human injury to time of accident, road conditions, road alignment, vehicle speed (via posted speed limits), number of vehicle occupants, and sex/age of moose struck…to develop measures to reduce MVCs and severity of injuries
- MVC reports from conservation officers and RCMP from 1988-1994…accidents generally reported if damage >$1000 CD ($500CD before 1991).
- Spatial analyses: N=1690 MVCs on Trans-Canada Highway, mapped/digitized, divided 900km of TCH into 90 10-km sections. category each section by
  - annual average MVCs (<1.75 = low, 1.75-3 = medium., and >3 MVCs = high)
  - moose density (<1.0 = low, 1-2 = medium and >2 = high)
  - traffic volume (low v high)
  - RESULTS:
    - Areas of low or high moose densies experienced greater probabilities of MVCs than areas of moderate moose densities.
    - Higher probability of MVCs in areas with high traffic volumes, regardless of moose densities
- MVCs and human injuries analyses: log linear modeling to evaluate effects of the following variables on severity of human injuries (low v fatalities)
  - darkness (day vs dusk/dawn/dark)
  - road condition (wet-slick vs dry)
  - road alignment (straight or curved)
  - vehicle occupants (driver only vs driver + passengers)
  - posted speed limits (<80km/h vs >80km/h)
  - passenger vehicles only (made up 89.5 of all reported collisions and had most serious injuries/fatalities)

- o determined influence of each variable on injury severity through forward model selection from main effects to saturated model…used log-likelihood value (G-sq) of main effects model (included all variables) as baseline against which all other parameters were judged…each 2-way interaction was then added to main effects model and tested. Deviance between baseline value and derived G2 stat measured importance of that parameter to model. Excluded parameters with small deviation, determined at 95% confidence level.
- o RESULTS:
  - *No significant relationship between road alignment and accident severity (though 79% of accidents occurred on straight vs curved roads)*
  - Model 1 (injury, darkness, speed): Light condition and posted speed limit related to severity, and mutually independent – *risk 2.1x greater at night and 2x higher at highway (high) vs non-highway (low) speeds.*
  - Model 2 (injury, road condition, occupants): more accidents occur than expected when passengers were in vehicles on dry roads, but not when there were no passengers or wet roads. *Risk of severe injury or death 2x higher w/at least 1 passenger present compared to driver only.*
- Also looked at temporal and age/sex influence…
  - o Moose calves more likely to be involved Aug-Oct, yearlings in June/July, and adults in July-Aug.
  - o More bull moose involved than exp.
  - o No significant relationship between diurnal patterns and sex or age.
  - o Injury 6x more likely in collision w/ adult than calf
- DISCUSSION points of interest beyond results:
  - o "Bashore etal 1985 found positive relationship b/w speed limit, driver in-line site visibility along road, and number of collisions (**see also Poll 1989)**.
  - o Damas & Smith 1982 estimate night speeds have to be reduced to 60km/hr or less under low-beam light to sufficiently expand stopping distances and prevent accidents…enforcement key and difficult/enormous…most effective measure may be with drivers"
  - o Lavsund and Sandegren 1991. Moose vehicle collisions in Sweden, a review. Alces 27:118-126.
    - "Lavsund and Sandegren (1991) found 3x increase in severity of injury for vehicles moving 70-90km/hr compared to lesser rates"
  - o Discussed PR programs, mentioned Terra Nova NP in Canada—long running program (12 yrs as of 2001) involving using moose silhouettes and posting of number of MVCs/year…have found Newfoundland drivers perceive TerraNova National Park as area with greatest number and risk of MVCs. See Hardy R.A 1984 resource management plan for MVCs, internal Terra Nova NP Parks Canada report.

Kassar, C., Bissonette, J.A. 2005. Deer-vehicle crash hotspots in Utah: data for effective mitigation. UTCFWRU Project Report No. 2005(1):1-28. Utah Cooperative Fish and Wildlife Research Unit, Utah State University, Logan Utah.

The data originate from collision reports prepared by law enforcement officers and provided to UDOT by the Utah Department of Public Safety. A wildlife-vehicle collision is included in the database only if an animal was actually hit, if the estimated vehicle damage exceeded $1,000 and/or if a person was injured. Collisions included in the database do not account for crashes that occurred as a result of swerving to miss an animal.

We focus on collisions involving almost exclusively mule deer. We used the UDOT vehicle crash database to study DVC patterns and trends from 1992-2002 on 248 state routes. We evaluated all routes for frequency of deer kills and identified "hotspots" (at least 1 collision/mile/year). We considered hotspots to consist of two parts: (1) a core area, the road segment where collisions per mile are most concentrated; and (2) a mitigation zone, buffering segments on each side of the core where appropriate mitigation actions can account for animal movement and behavior and help avoid the "end of the fence" problem.

Summary of results: 24,299 WVC over 11 years; 99.6% had dates and years associated with them; average of 2,202 (2,025-2,577) collisions per year; 12 routes had high DVC rate over entire length ($\geq$10/mile); 16 with moderate (5-9.99/mile); 148 with low rates (>0-4.99); 65 routes with no reported DVC; 7 with data unavailable; 54.6% of all collisions occurred on 10 routes

Collision frequency: 0-21.27 per mile; 1/3 occurred Oct-Dec; 55.7% occurred 1800-2400 hr

Hotspots: found 183 hotspots in Utah; core hotspots average 5.3 miles in length; isolated hotspots were 1 mile (1.6 km) in length; hotspot collisions were concentrated; 57.74% of all collisions occurred within a cumulative,~1001 km, range, or 10.5% of total analyzed highway miles (9,500 total km)

Malo, J.E., Suarez, F., and A. Diez. 2004. Can we mitigate wildlife-vehicle accidents using predictive models? Journal of Applied Ecology 41: 701-710.

Objective: the present study analyzed a European case and developed models of the environmental variables associated with the occurrence of collisions with animals at two spatial scales (1.0 and 0.1 km). Provided that a few variables underlie the location of animal crossings, it should be possible to predict where accidents may occur and use this information to optimize mitigation efforts. With this aim, we (i) defined road sections with high collision rates using a **clustering detection procedure**; (ii) analysed the landscape variables of sections with high collision rates

in contrast to low collision sections; and (iii) use a 0.1 km scale to analyse the points where collisions occur in contrast to those where they do not.

Data layers: official traffic database on WVC for Jan 88-Feb 01; n=2,067; includes date, location (0.1 km); 63% of WVCs occurred between 1998-2001; 98% involved roe deer, wild boar or red deer

- Definition of high accident rd sections: determined by detecting clusters of WVC locations; contiguity analysis conducted by comparing the spatial pattern of collisions with that expected in a random situation; each km of rd with 3 or more collisions, especially over consecutive km, could be defined as a high collision section
- 1:50,000 digital forest cover map (cover types used: riparian forest, other forest, scrub, grassland, crops, rivers and dams, urbanized and unproductive); processed in ArcView 3.2
- Habitat features in high collision sections: analyzed 84 locations-41 high collision, 43 low collision; sampling unit=circular area (radius 1000m) around reference point; calculated proportion of each habitat type; ecotone length (meters of contact lines between habitat polygons); habitat diversity (Shannon index)
- Variables associated with collision point: analyzed at 0.1 km scale: sampling points from 18 high collision sections in which WVCs had been recorded in at least 12 hectometer posts; 6 hectometer posts with highest number WVCs chosen from each section; a further 6 taken at random from amongst those with recorded collisions; 12 control samples w/o WVCs taken at random from each section
- Evaluated 13 quantitative and 15 qualitative variables covering aspects linked to driving, general features of the road environs, features associated with animal movements; measurements taken for 100m rd stretch and evaluated 100m on each side of road

Analysis: analyzed at both regional and local scales; predictive models for the location of sections/points with and without collisions were generated by binary logistic regression; validated with independent data

- 2 models fitted for each analysis: 1 complete with all measured variables, 1 reduced version with only most significant explanatory variables
- variable selection for reduced models using G^2 statistic; ensured new model was not significantly more informative than previous one, avoided correlated variables and those w/o predictive capacity
- significant threshold in variable comparison: P=0.05; probability threshold for model: P=0.1

Results landscape scale: 41 high collision rd section identified; 7.7% of rd network accounting for 70.5% of all records; distributed among secondary and tertiary roads; none along A-2 fenced motorway

- High collision areas had higher cover of non-riparian forest, lower crop cover, lower urbanized areas, and higher habitat diversity than low collision areas
- Simplified model included forest cover, urbanized area and habitat diversity; had same predictive capacity as full model: 87.0% correct classification for all cases, 88.5% for high and 85.7% for low collisions sections; successfully predicted 70% of 30 cases used as test data

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Results for local scale: low collision areas associated with crossroads, underpasses, guard rails, embankments at least 2m high with moderate or steep slopes, greater distances from roads to hedgerows and forest stands, and shorter distances from roads to buildings

- Reduced model included presence of crossroads, presence and continuity of guardrails, presence and continuity of embankments and distance to nearest forest stand; correctly predicted 61.2% of cases, 72.7% of collision points, 48.4% of non-collision points; full model results were 74.0%, 79.2% and 68.1% respectively; correctly classified 64.2% of test cases

Discussion: results show it is possible to predict the location of WVCs at 2 scales; results showed be considered cautiously; validity could be hindered by assumption of a binomial distribution of errors-bigger issue for local rather than landscape model

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Nielsen, C.K., Anderson, R.G., and M.D. Grund. 2003. Landscape influences on deer-vehicle accident areas in an urban environment. Journal of Wildlife Management 67(1): 46-51.

Objective: quantified the effect of landscape factors on DVA in 2 Minneapolis suburbs to provide public officials and wildlife managers with recommendations for managing the landscape to reduce DVA.

Data layers: digitized DVA locations from 1993-2000 using ArcView

- DVA **clustering** to differentiate DVA areas ($\geq$2 DVA) and control areas (0 or 1 DVA); overlaid 0.5 km road segments at midpoint of DVA clusters; buffered road segments for variable selection purpose with a 0.1 km perpendicular distance from edge of each side of road; repeated for control areas (n=160 total)
- Landscape variables: land cover (grassland/residential, woodland, open water); land-use (commercial/industrial, residential, public land); ArcView Patch Analyst used to calculate 60 class and landscape level variables; road curvature (straight or curved); number of buildings in buffer, speed limit; number of lanes; distance from road to nearest forest cover patch; ROW topography based on presence or absence of ditches

Analysis: univariate procedure used to reduce 66 variable set to smaller group; removed variables correlated at r$\geq$0.70; left with number of buildings, number of forest cover patches, proportion of forest cover, Shannon's Diversity index for further analysis

- Logistic regression analysis to determine which variables best explained difference between DVA areas and control areas; built one global model and 10 a priori models; used AICc and Akaike's weights to rank and select best model; used relative weight of evidence to compare parameter importance; model averaging to incorporate model-selection uncertainty into final unconditional parameter estimates and standard errors.
- 40 sites retained to validate best fit model

Results: global model was significant; areas with DVA contained fewer buildings, more patches and higher proportion of forest cover, more public land patches and higher

Shannon's diversity index of landscape; Akaike's weights indicated number of buildings and number of public land patches most important variables
- 7 models necessary to compile a 95% confidence set; best-fit model correctly classified 77.5% of test sites

Discussion: study unique because assessed landscape factors influencing DVA in an urban environment; pooled data over 7-year period so pop growth or land-use change may have affected data

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Nielsen, S.E., Herrero, S., Boyce, M.S., Mace, R.D., Benn, B., Gibeau, M.L., Jevons, S. 2004. Modelling the spatial distribution of human-caused grizzly bear mortalities in the Central Rockies ecosystem of Canada. Biological Conservation. 120:101-113

Objective: We develop predictive models and maps that describe the distribution of human-caused grizzly bear mortalities…Our goal was to understand, through modelling, the relationships among bear mortality locations and landscape-level physiographic and human variables. More specifically interested in (1) examining the spatial density of grizzly bear mortalities; (2) evaluating possible differences in the physiographic attributes of mortality locations…; and (3) developing predictive models that estimate the relative probabilities of bear mortality (risk) given multivariable combinations of physiographic variables.

Data layers: mortality info from 1971-2002; included dead bears and translocated bears; location (UTM when possible), accuracy of location (accurate, reasonable, unknown), month, year, sex, age, and cause of mortality; n=279 accurate and reasonable locations
- GIS (spatial) predictor variables: land cover (Landsat TM 95-98, 5 classes); distance to edge of nearest land cover; greenness index; distance to nearest water feature; distance to nearest linear human use feature; terrain ruggedness index

Analyses: 3 separately scaled **moving windows** to calculate total density of mortality locations: 520 km^2; 900 km^2; 1405 km^2; secure sites=pixels with 0 mortalities; high mortality zones=pixels with >31 mortalities ($\geq$1 mortality/year)
- Logistic regression to assess relationship between landscape attributes of mortality locations and categories of demographic status, season, and mortality type
- Random sample of locations generated to contrast with human-caused mortality locations
- Data divided into model training (80%) and model testing (20%) data sets
- Logistic regression used to contrast the location of grizzly bear mortalities with sites used by bears (through telemetry)

Results: mortalities concentrated within 3 regions regardless of scale examined
- 900 and 1405 km^2 scales: mortality densities within moving windows exceeded 31 mortalities for the three sites; at 520 km^2 scale: only one site as high mortality zone

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- Total area occupied in high mortality zones: 520 km^2 =1.4%, 900 km^2=3.8%, 1405 km^2=13.2%
- Total area occupied in secure zone: 520 km^2=23.9%, 900 km^2=13.9%, 1405 km^2=23.9%; 22-32% secure habitat in areas of non-habitat
- Mortality locations positively associated with access, water, and edge features; negatively associated with terrain ruggedness and greenness indices
- Non-harvest mortalities more likely to occur in shrub and grassland habitats and close to edge features and access than random points
- Mortalities more likely to occur in deciduous forest and shrub habitats, nearer to edge, access, and water than radiotelemetry locations; also sig related to areas of low greenness and minimal terrain ruggedness

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Premo, D.B.P., Rogers, E.I. 2001. Town of Amherst deer-vehicle accident management plan. White Water Associates, Inc., Amasa, Michigan (http://www.white-water-associates.com)

Objective: This plan's focus is reducing DVAs. The primary measures of concern are the numbers of DVAs and the patterns of their distribution in the Amherst landscape. The DVA Management Plan establishes its initial goal at two spatial scales, whole town and hotspots.

Data layers: DVAs reported to police (n=3300) and counts of carcasses removed from road (n=3320); Jan 1991-Dec 2000; entered into GIS; time of day, time of year, location, speed limit, landcover; deer population; management zones

Analyses: **density analysis** in ArcView used to examine landscape patterns of DVAs. This allowed mapping of DVAs as density contours and identification of DVA hotspots; density calculated by circles of half-mile radius; DVA density=DVA/sq. mi.; when displayed in conjunction with other mapped features, contours could be used to determine the causes of the hot spots as well as examine temporal changes

Results: temporal changes in hot spots before, during and after the concentrated lethal control period

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Rogers, E. 2004. An ecological landscape study of deer-vehicle collisions in Kent County, Michigan. Report for the Michigan State Police, Office of Highway Safety and Planning. White Water Associates, Inc., Amasa, MI 49903. 56 pp.

Objective: an analysis of landscape patterns of DVCs in 4 townships of Kent County, Michigan

Data layers: GIS database available; included spatial layers drawn from MiRIS Base Maps and Land Cover Maps; political boundaries, land survey section lines, transportation, watercourses and lakes, major veg cover types, development

DVC locations from Michigan Accident Location Index (MALI) maintained by Michigan State Police, 1992-2000; locations based on police reports; uses system of unique physical reference numbers to spatially record accidents

N=3127 DVC records coded by township, year, month, time of day

Half mile grid created in ArcView and superimposed on study area for summarization of landscape data; ½ mile chosen because of assumed low precision in DVC location data; grid split into two equally sized groups of cells, 1 group for model development, 1 for validation

Density function in Spatial Analyst used for visual inspection of DVC patterns; density calculated for each cell by summing number of DVCs found within search radius (1/2 mile) and dividing by the area of the circle

Stepwise logistic regression to identify a subset of parameters to build predictive logit model; final model had 3 parameters: linear feet of highways and roads, linear feet of roadway within 1000ft of watercourse, number of mapped land use polygons

Analysis: mapping of DVC densities summed across all years; mapping in 3 year blocks; resulted in very little change in hotspots across years, only minor shift in location and density

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Romin, L.A. and J.A. Bissonette. 1996. Temporal and spatial distribution of highway mortality of mule deer on newly constructed roads at Jordanelle Reservoir, Utah. The Great Basin Naturalist 56(1): 1-11.

Objectives: 1) to determine whether mule deer roadkills on newly relocated highways would increase, 2) to evaluate the influence of topographic features and vegetation characteristics on the kill pattern

Data collected from 15 Oct 1991-14 October 1993; 47.3 km total on 3 highway segments; road construction completed in 1989

Data layers: deer roadkill data collected at least once per week (date, highway identification, location to nearest 0.10 mile, age class);
- 4 randomly selected pairs of kill (5 or more kills/mile) and non-kill zones of 0.10 mile road length each; for each pair, established 3 transects perpendicular to road, 100m apart, extended 100m beyond ROW fence to evaluate respective road alignment and associated habitat features
- distribution of kills (nearest 0.01 mile); avg traffic volume and speed for each highway; % vegetative cover; topography proximal to area roads; twice monthly spotlight counts of deer (sex, age class, activity, location to nearest 0.10 mile); deer snow track counts (number of trails, orientation relative to road-parallel vs perpedicular); observable area from highway every 0.1 mile; right-of-way width and slope; ROW vegetation; vegetation composition; road type

Analysis: Stereoscopic aerial photography used to describe habitat features; transparent grid placed over photos to determine percent cover and topographic features at deer-highway mortality locations beginning at the road and extending 1.2 km distant; identified roadkill and live deer locations, as well as descriptive roadside features to 0.1 mile

Results: 397 deer roadkills during 2 years of study; deer kills averaged <20 before roads relocated; 19 deer kill zones identified; deer spotlight counts not significantly correlated with kill sites; kill zones had higher mean % cover

Discussion: traffic volume significantly influenced deer mortality; higher kill levels occurred along drainages; ROW topography may funnel deer to the ROW and encourage movement along highway corridor

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Seiler, A. 2005. Predicting locations of moose-vehicle collisions in Sweden. Journal of Applied Ecology 42: 371-382.

Objective: to develop MVC prediction models based on data that are readily available for road planning at strategic and project levels (Seiler and Eriksson 1997). This study used accident statistics from before 1999, remotely sensed landscape information, digital topographic data and official road and traffic data to identify the strongest set of environmental and road traffic parameters that can be used to foresee the risk of MVC.

Data layers: Landscape, road and traffic, collisions, moose abundance and harvest
- Landscape data: Swedish Terrain Type Classification maps (TTC) (based on SPOT and Landsat TM satellite images) combined with digital topographic maps at a scale of 1:100,000; 1994-1998, updated with aerial photographs from 1999
  - 25x25 meter pixel size; 6 major land cover types; densities of landscape features measured as km per km2, number of intersections per km rd; distances between rd and landscape elements measured in meters and log(e) transformed
- Road and traffic data: from digital road databases provided by the SNRA
  - Averaged rd density: model area-1.92km/km2; test area-1.76 km/km2; 75% is privately owned
  - National trunk roads: 2,500-20,000 vehicles/day; >90kph; Tertiary public roads: 80% of rd network, <1,000 vehicles/day, <70kph; Primary roads (speed limit >90kph) in model area 71% fenced, in test areas 35% fenced
  - Average number of vehicles/day used jointly with its square to adjust for the humpbacked relationship between traffic volume and MVC frequencies observed in the data
- Moose-vehicle collisions: obtained from the SNRA rd acc stats containing all police-reported accidents on public rds between 1972-1999 (type of accident, place, time)
  - Accuracy not evaluated, error estimated at $\pm$500 m (L. Savberger, pers com).
  - N=2185 for model area; N=1655 for test area (for 1990-1999)
- Moose abundance and harvest: indices of moose abundance were determined from the average annual game bag per hunting district during the 1990's
  - Model area: 21 hunting districts, avg 3.45 shot/1000 ha (1.0-5.1); Test area: 14 hunting districts, avg 4.25 shot/1000 ha (1.6-6.4)

- o Moose harvest and MVC correlated strongly at county and national levels over the past 30 years (Seiler 2004)
- o No migration between winter and summer ranges

Analysis: 3 logistic regression models were developed to identify parameters that significantly distinguished between observed MVC sites and non-accident control sites

- Model composition: N=2000 MVC records, N=2000 randomly distributed non-accident control sites located at least 1km away from MVC site
  - o 500m buffer created around each point (to account for estimated error)
  - o unpaired t-tests and univariate logistic regression models used to identify among 25 variables those that sig (P<0.1) differed between accident and control sites (all other analyses used P<0.05); intercorrelated variables removed, 19 variables left
  - o 3 a priori models: 1) road-traffic (only basic road and traffic parameters); 2) landscape (parameters obtained from RS landscape data and digital maps); 3) combined model
  - o stepwise (backward) regression to identify sig parameter combos; sets compared using AIC and Akaike weights; model structure considered adequate if variance inflation factors were close to 1.0
- Model validation: N=1300 accident sites (1km road sections) and 1300 non-accident sites (1km road sections) from new county; 500 meter radius around the center point of each road section; univariate logistic regression analyses to determine model performance in distinguishing accident from non-accident sites
- Counteractive measures: to illustrate and evaluate the predicted effect of different counteractive measures on accident risks, changes in MVC probabilities relative to varying traffic volume and moose abundance modeled with respect to increased forest proximity, reduced vehicle speed and road fencing.

Results: Dominant factors determining MVC risks included traffic volume, vehicle speed and the occurrence of fences

- Model results: model ranking according to AIC weights: 1) traffic (classified correctly 81.2% of all observations), 2) combined (83.6%, but lower ranking because of greater number of variables), 3) landscape (67.5% MVC sites and 62.2% control sites)
- Validation results: combined model gave best results predicting 72.4% of all MVC sites and 79.8% of all control sites; traffic model concordance = 77.9%; landscape model concordance = 62.0%; all results are significant
- Identified 72.7% of all accident sites
- Other parameters were important in distinguishing between accident and control sites within a given road category including amount of and distance to forest cover, density of intersections between forest edges, private roads and the main accident road, moose abundance indexed by harvest statistics
- Together, road traffic and landscape parameters produced an overall concordance in 83.6% of the predicted sites and identified 76.1% of all test road sections correctly
- Speed reduction appeared to be most effective measure to reduce MVC risk at any given traffic volume; modified by fencing, moose abundance and forest proximity

Discussion: spatial distribution of MVC not random; collisions a product of environmental factors quantified from RS landscape info, road traffic data and estimates of animal abund.; parameters used to identify high risk roads (traffic data) different from parameters used to identify high risk road segments (landscape data)

Simek, S.L., Jonker, S.A., Endries, Mark J. 2005. Evaluation of principal roadkill areas for Florida black bear. ICOET 2005.

Principal road-kill areas (PRA) defined as 3 or more roadkill bear within a distance of 1 mile (1.6 km)

Data from 2001-2003 analyzed using density analysis with Spatial Analyst in ArcGIS

6 core and 2 remnant black bear populations evaluated

Objectives: to establish whether previously identified 'chronic' areas were still apparent or had shifted, and whether different criteria and time frames would impact results and subsequent conservation recommendations using current and previously evaluated roadkill data

Data layers: FWC bear roadkill data and the major roads shapefile (interstates, state highways, county highways, highways access ramps, and major local and forest roads)

Density analysis: raster format with 30m x 30m pixel size; creates a 2D raster grid of pixels calculating the total number of points that occurred within the search radius divided by the search area size; pixels within areas meeting principal roadkill definition reclassified to 1 (referred to as CRDA), all others classified as no value; one mile buffer created around CRDA dataset (referred to as PRBA); analysis repeated using criteria outlined by Gilbert and Wooding (1996) of 8 roadkill bear/7 miles (they used dataset from 1976-1995)

Results: With a few exceptions, most of the PRA identified by both methodologies overlapped; Gilbert methodology encompassed a much larger area which included more roads whereas the current methodology identified more specific principal roadkill road segments; using similar timeframe (1976-1995), two methods again identified very similar PRA but new method identified additional areas; using complete timeframe (1976-2004) PRA identified in all 6 populations, including 2 which had not been previously identified as containing PRA

Discussion: illustrated that changes in locations of PRA can occur when using different methods and timeframes; different results with respect to scale-Gilbert's method gives PRA on a broader scale, new method provides increased specificity on actual locations of 'hotspots'; PRA will change with changes in habitat and land use; preferred method (Gilbert or new) will depend on goals and objectives

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Singleton, P.H., Lehmkuhl, J.F. 1999. Assessing wildlife habitat connectivity in the Interstate 90 Snoqualmie Pass Corridor, Washington. ICOWET III

Objective: an assessment of wildlife habitat connectivity and barrier effects of I-90 from Snoqualmie Pass to Cle Elum was initiated in January 1998. The assessment consists of 5 components including a GIS analysis of ungulate road-kill distribution

Data on ungulate roadkill locations was collected by WSDOT maintenance personnel from 1990 to 1998. We imported these records on species and location of roadkills into the GIS and used a moving window analysis to determine the number of kills per mile along I-90

Results: 4 roadkill concentration areas were identified based on the analysis of 490 deer and 194 elk kills. Quantitative analysis of landscape characteristics of collision locations has not yet been conducted. However, roadkill distribution appears to be affected by landforms that channel animal movement and by human development and disturbance patterns.

II. SPATIAL ANALYSIS TECHNIQUES

Boots., B.N. and A. Getis. 1988. Point Pattern Analysis. Sage Publications, Inc. Newbury Park, California. 85 pp.

- Development of statistical analysis of point patterns originated in plant ecology over 50 yrs ago.
- Point pattern map has 2 components:
  - Point pattern: has size (# points, n)
  - *Study area: may be 1 or multidimensional. Roads would be represented as a one-dimensional study area. Two dimensional study areas are enclosed by a boundary, which determines the shape of the study area. Road study areas do not have a shape necessarily.*
  - If studying *the location of points relative to the study area, then examining dispersion of points, if studying locations of points relative to other points, then examining the arrangement of points. In many cases dispersion and arrangement may be highly correlated*
- When analyzing pt patterns, usually use method that involves establishing a theoretical pattern that is compared to other patterns that are identified. That theoretical pattern chosen is formally called a homogeneous planar Poisson point process, and these points are generated under two conditions:
  - Each location has equal chance of receiving a point (uniformity)
  - Points selected do not influence the selection of other locations for points (independence).
  - These conditions imply the study area is homogeneous w/no interaction b/w points, and the resulting pattern from that point generation process could be considered to occur by chance in an undifferentiated environment, referred to as "complete spatial randomness" or CSR (cites Diggle 1983)
  - CSR is idealized standard which other patterns can be compared to—

- Clustered patterns occur when points are significantly more grouped in the study area than they are in CSR.
- Regular patterns occur when points in the study areas are more spread out than they would be in CSR
  - o Opposite of uniformity condition/homogeneous model: heterogeneous models, which imply some locations in study area are more prone to receive a point than other locations, or may be less likely to receive a point.
  - o If independence assumption is relaxed, then there may be interaction among points – i.e., they may attract or repulse each other.
  - o To analyze dispersion or arrangement characteristics, use hypothesis testing procedures, with the null hypothesis always that the pattern is CSR, with the simplest alternative hypothesis being that the pattern is not CSR.
    - If null not rejected, no further analysis needed.
    - Null (CSR) provides division between clustered and regular patterns
    - If null is rejected, can develop further formulate new null hypotheses to test other theories.
- Spatial autocorrelation is a measure of the correlation among neighboring points in a pattern.
  - o No spatial autocorrelation means no correlation between neighboring values and would expect CSR
- Measures of dispersion/distance methods analyze patterns using stats calculated using characteristics of distances separating individual points in the pattern.
  - o Nearest neighbor analysis (NNA):
    - as originally developed, several limitations – Inaccuracy in interpretation in some situations and edge effects
    - 2-d study areas (not roads): defined as distance between point a and the nearest other point in the pattern
    - Distances other than those between a point and its closest neighbor are refereed to as second, third, or "higher order neighbor distances"
    - NNA in 1-d study areas (roads): same concepts, but the line is bounded by its ends, so two ways to deal with these ends (edges)
      - If points at ends of line
      - If no points at either end of the line
      - NN dist for any point not located at an end point is distance to either the preceding or succeeding point encountered on the line; thus nearest neighbor distances are part of the set of all interpoint distances on the line. To test, interpoint distances converted to proportions of the sum of the interpoint disances, resulting in scaled values ranked from smallest to largest, within n as the number of interpoint distances. Observed and expected values compared to normally distributed statistic z; if calculated value of z is positive and larger than vaue of z=1.96 (alpha 0.05)

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obtained from tables of normal dist, the null is rejected in favor of hypothesis that indicates regularity in the point pattern.

- Refined NNA (cites Diggle 1979 pg 79) involves comparing the complete distribution function of the observed nearest neighbor distances $F(d_i)$, with the distribution function of expected nearest neighbor distances for CSR $P(d_i)$.
    - Observed nearest neighbor distances obtained by taking nearest neighbor distances and ranking smallest to largest, then determine what proportion $F(d_i <= r)$ of nearest neighbor distances are less than or equal to some chosen distance r (usually selected to correspond with nearest neighbor distance values).
        - Cited Pielou (1969:111-112) with equation that shows that the corresponding proportion of expected nearest neighbor distances < or = to r for unbounded CSR pattern. $P(r)$
        - Diggle 1981 suggests $P(r)$ and $F(r)$ can be compared using $d_r = \max | F(r)-P(r) |$
    - Because nearest neighbor distances are not mutually independent Diggle (1981:26) suggests to evaluate the significance of d_r, use Monte Carlo test procedure to generate set (usually 99) of CSR patterns each with the same number of points as the empirical pattern in the study area, then calculate d_r for each of the calculated simulated patterns, then examine where the value of d_r for the empirical/observed pattern falls within the entire set of 100 values (99 simulated and 1 observed patterns). If d_r for observed pattern were among 5 largest values of d_r, the null of CSR can be rejected (at alpha 0.05). Diggle 1979 suggests that if for d_r, $F(r)>P(r)$, then clustered, whereas if $F(r)<P(r)$ than indicates regular pattern of points.
- Second order procedures requires distance measurements between all combinations of pairs of points. Study of interevent distances where events are mapped points. Focus is on the variance, or second moment, of interevent distances.
    - Advantages over other techniques: more info about pattern is potentially available; CSR model available for interevent distances can be used as basis for statistically significance (2nd order analysis); statistically defensible boundary correction technique developed for 2nd order studies. Convenient to use to study various distance subdivisions or distance zones.
    - Analysis based on circle with radius d centered on each point, each of the points w/in the circle is paired with the center point of that circle and it is this number of pairs that form our data. As d increased, see increased number of pairs of points in each circle. Analysis of that data depends on expected pairs of points derived similarly to points in a Poisson process (CSR model). Ripley (1981:159-60)

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- - Cites Haining (1982), Getis (1983, 1984), Ripley 1981 and diggle 1983 additional background.
- Measures of arrangement examine locations of points relative to other points in the pattern. Two advantages over measures of dispersion:
  - Advantages
    - "density free": to compare arrangement properties of CSR pattern against observed pattern, don't need to estimate any values from the observed data.
    - Arrangement measures are concerned with the locations of points relative to each other and not relative to the study area (as is the case with dispersion methods)
  - Disadvantage:
    - Not as rigorous than measures of dispersion, sort of like how non parametric statistics are usually less powerful than their parametric equivalents;
    - Measures of arrangement are insensitive to some differences in some pattern characteristics so that identical values may be expected for patterns that are different in some way.
    - Stats theory less well developed (in 1988) so greater element of subjectivity enters when interpreting results of analyses of measures of arrangement.
  - Reflexive nearest neighbor analysis:
    - When two points are the nearest neighbor of each other, said to be reflexive (reciprocal) nearest neighbors.
    - Test number of reflexive nearest neighbors in the pattern observed compared to expected number of reflexive nearest neighbors in CSR.
    - Lack of a test of significance and unanimity in interpreting results…common to extend analysis to analysis of reflexive nearest neighbors to higher orders; in interpreting number of observed pairs in relation to CSR values, most researchers suggest that higher order values in excess of the SCR expectations indicate a measure of regularity in the arrangement of points whereas lower empirical values imply grouping.
    - Dacey 1969 gives tables of probabilities that a point along a line in a random pattern is the jth neighbor of its own j^{th} nearest neighbor for $j <= 6$. 1st order prob: 0.6667; 2nd order prob: 0.3704; 3rd order prob: 0.2716; 4th order prob: 0.2241; 5th order prob.: 0.1952; 6th order prob.: 0.1753…….to get "expected" multiply total number of points that are by the corresponding probability, and if observed number of jth pairs is less than expected, then suggests grouping
    - May be that the reflexive nearest neighbor observed = CSR, but when look at higher order reflexive pairs (2nd, 3rd, etc) may see tendencies toward grouping.
- Summary: No one single optimal method.

- Power of most point pattern techniques (i.e., ability to eliminate false hypothesis) varies depending on the type of pattern so some techniques are better than others in detecting clustering whereas others are better at detecting regularity.
- Measures of dispersion better than measures of arrangement since the latter methods require more subjectivity in the interpretation of their results.
- Measures of dispersion used in combo with arrangement techniques can provide confirmation of results and further insights into the patterns

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Burka, J., D. Nulph, and A. Mudd. 1997. Technical approach to developing a spatial crime analysis system with ArcView GIS. INDUS Corporation and U.S. Department of Justice.

- Discusses methods used to develop and implement an ArcView based spatial crime analysis system for geographic analysis.
- Sample application functions include
    - Pin maps and summaries
    - Geocoding
    - Change maps that look at trends over time based on two maps of same area representing incidents at different times, which produces a third map that shows increase or decrease in incidents per polygon b/w the two time periods.
    - Surface-derived hot-spots – many ways to do this, but they use ArcView spatial analyst to build a surface of incident density for a selected set of incident pts, using the kernel function in Spatial Analyst, then reselect out the "peaks" depicting hotspots
    - Standard deviation Ellipses
    - Temporal and spatial trend charts
    - Layout generation (maps)

Lee, J. and D.W.S. Wong. 2001. Statistical Analysis with ArcView GIS. John Wiley and Sons, Inc., New York, New York. 192 pp.
- Chapters:
    - Attribute Descriptors
    - Point Descriptors
    - Pattern Detectors
    - Line Descriptors
    - Pattern Descriptors

Levine, N., K.E. Kim and L.H. Nitz. 1995. Spatial analysis of Honolulu motor vehicle crashes: I. Spatial Patterns. Accident Analysis and Prevention 27(5):663-674.

- Examines method for geo-ref crash locations and tools for describing spatial dist of crash locations, and how types of crashes can be spatially differentiated. Study area was assumed homogeneous planar, not a network (system of roads).
- 4 general categories of analyzing spatial variations in auto crashes:
  - Diff types of environments – rural v urban, large cities v small cities, state comparisons, national comparisons; tend to use highly aggregated data and large geographical units
  - Examines crashes as function of volume, speed, other variables on roads, road types, intersections, emphasis on functions of the road system, how different road segments or elements create different crash likelihoods. Classic "blackspot" analysis included in this category (cites: Boyle and Wright 1984, Persaud 1987, Maher and Mountain 1988)
  - Crashes in particular areas, corridors, neighborhoods, emphasis on analysis units, which are socially and ecologically integrated.
  - System wide spatial variations in crashes (few studies on this) to look a variations across region, examine how crashes I a particular zone or sub area are part of larger spatial pattern
- Developed own software to derive different indices of spatial point pattern (Hawaii Pointstat; cites Levine et al 1994). Takes list of lat/long for each crash location and produces 4 measures of concentration
  - Mean center (mean lat and mean long on list, "center of gravity")
  - Standard distance deviation, based on "Great Circle" distance of each point from mean center (cites McDonnell 1979 chap 1; Snyder 1987 pp. 29-33).
  - Standard deviational ellipse, which calculates the SD along a transformed axis of maximum concentration and another SD along an axis which is orthogonal to this (cites Ebdon 1985 pp. 135-141). More concise than standard distance deviation circle (above).
  - Nearest Neighbor Index, which measures average distance from each point to the nearest point and then compares this to a distribution that would be expected based on chance. (cites Ebdon 1985 pp143-150; Cressie 1991 pp602-615). Developed by plant ecologists for describing clustering of point patterns (cites Clark and Evans 1954). For each point, distance to every other point calculated and shortest distance selected, then shortest distances are averaged and compared to a NNDist which would be expected based on chance (Nearest Neighbor Index). Index of 1.0 is indistinguishable from chance, lower than 1.0 indicates clustering and >1.0 indicates dispersion.
  - These measures allow description of spatial variation and degree of concentration (spatial autocorrelation).

- Compared SD ellipses for types of crashes (fatal, serious injury, alcohol-related, single vehicle, head on, two vehicle..etc.) to e/o as well as to other ellipses for residential population and employment.
- Used to provide insights into how certain relationships have a spatial dimension (e.g., between alcohol and severe injuries; types of impact and injury level), can be used to compare diff types of accidents, the same type of accident for 2 diff time periods, or same type for two different areas. These do not provide behavioral insights.
- These methods go beyond *"blackspot" analysis…blackspot analysis assumes that observation locations are spatially independent; that each observed location has its own random process, whether Poisson distributed or not. Cites Loveday and Jarrett 1992 re: spatial autocorrelation and that you cant treat each observation as independent.*
- Limitations to these tools: assume monocentric spatial plane but in cities often have multiple centers and these distort the relationships by assuming a center, but they say that there are no accepted methods for identifying multiple nodes in a spatial plane; most cluster analyses produce biased results since they don't take spatial autocorrelation (see Anselin 1995 for developments in this area).

Levine, N. 1996. Spatial statistics and GIS: software tools to quantify spatial patterns. Journal of the American Planning Association 62(3): 381-391.

- Reviews the following software tools:
  - STAC (Spatial and Temporal Analysis of Crime):
  - Hawaii Pointstat
  - S-Plus
  - Venables and Ripley Spatial Statistics Functions.
  - SASP: A 2-D Spectral Analysis Package for Analyzing Spatial Data
  - SpaceStat: A Program for the Statistical Analysis of Spatial Data
- Variables may be described spatially as either
  - Occurring at unique point locations (incidents, buildings, people)
  - Aggregated to areas (census tracts, traffic analysis zones, city boundaries)
- Stats describing points or areas fall into 3 general categories
  - Measures of spatial distribution, which describes center, dispersion, direction, and shape of the distribution of a variable (cites Hammond and McCullogh 1978; Ebdon 1988). E.g., get latitude/longitude locations geo-coded, then can calculate center of the distribution ("center of gravity" or mean center), dispersion (standard distance variation), direction of the dispersion (standard deviation ellipse) – then can compare to other distributions.
  - Measures of spatial autocorrelation describe relationship among different locations for a single variable, indicating degree of concentration or dispersion (cites Cliff and Ord 1981; Haining 1990; Cressie 1991).

Indicates whether clustering is greater than can be expected on basis of chance.

- o Measures of spatial association between two or more variables, describes the correlation or association between variables distributed over space (Anselin 1992b spatial dependence article)

- STAC Spatial and Temporal Analysis of Crime DOS based program designed by Statistical Analysis Center of the Illinois Criminal Justice Information Authority to help police depts. Identify small concentrations (called "hot spot areas") of crime.
  - o Two modules – TIME, SPACE. SPACE module does two things: radial search for incidents from a selected point and identification of highest concentrations of incidents within a study area. SPACE needs identification number and X, Y location of each point in Euclidean coordinates (plane coordinates, UTMs). Must specify limits of study area (min/max X, Y coordinates) as well as search radius which is a circular area that the program uses to search for points that cluster together. No theoretical basis for choosing particular radii and different search radii will produce slightly different clusters. Produces ellipses to identify areas of clustering. Doesn't have statistic to objectively group points into unique clusters (i.e., with fixed number of clusters and each pt assigned to one and only one cluster).
- Hawaii Pointstat provides summary measures of the spatial distribution of points. Available in DOS and Sun Unix versions, can be obtained from the Internet.
  - o Takes list of x,y location points, can use weights/intensities for points (i.e., if multiple WVCs occurred at same location). Distances between points calculated with 2 different metrics
    - ▪ Spherical geometry using "great circle" distances;
    - ▪ Spherical grid distances, which assume that travel occurs only in horizontal or vertical direction (not diagonally) – used in cases of grid street systems.
  - o Program produces following outputs: mean center; standard deviation of distance of each point from mean center; standard deviation of ellipse (which is 2 standard deviations, one along a transformed axis of maximum concentrations and one along an axis 90 degree to that other axis, defining an ellipse); nearest neighbor index; Moran's I (Moran 1948, 1950; Ebdon 1988, Haining 1990)
  - o Provides summary stats of point spatial distributions and can output distance files for use in other programs. Useful to describe distribution of points and can be used to compare different types of distributions.
- Venables & Ripley's Spatial Statistics Functions in S-Plus: modules written in S-plus (distributed by StatSci), available in both Unix and Windows systems. Has Ripleys K function utilities…Ripley's K-function uses distances between all points and compares the observed number of neighbors within a certain distance to a theoretical number based on a Poisson random process…k-fx generally considered most comprehensive of the distance measures and can be used for determining the distance scale at which randomness occurs

- SASP – two dimensional spectral analysis package for analyzing spatial data – set of utility modules for conducting 2-d spectral analysis using a grid cell organization (Renshaw and ford 1983; Ford and Renshaw 1984; renshaw & ford 1984) 2-d spectral analysis is technique for detecting patterns in a spatial distribution and is direct extension of 1-d spectral analysis used in time series analysis.
  - o Data consist of series of rectangular grid cells imposed over spatial plan with m rows and n columns. The value within each cell represents an estimate of a third variable, which could either be number of discrete points that fall within the cell or a value attributed to the entire cell.
  - o "Distribution of grid cell structure can be decomposed into trigonometric ("cyclic") components, called a Fourier decomposition… resulting in discrete frequencies (p & q) that are independent of e/o and that indicate the contribution of each frequency to the overall pattern. Essentially an ANOVA splitting up the variance into sine/cosine components.
  - o Central output is periodogram which is a plot of the sine/cosine components and is expressed as the number of waves down the rows, p, and the number of waves across columns, q, with an origin at p=0 and q=0. Two summary indices: R-spectrum is average of periodogram values for semicircular "distance" bands emanating from the origin (p =0, q=0) and a width of 1. The θ spectrum is an average of the periodogram values for an angular band (i.e., pie slices) from the origin; that is, it is a polar coordinate band that is 10 degrees wide, starting at -5 deg -+5deg along the x-axis and turning clockwise until 165-175deg.
  - o Also 3d figure showing a smoothed rearranged periodogram
  - o 2d spectral analysis seen as exploratory tool for examining repeating spatial patterns.
- SpaceStat program designed to spatially analyze areal distrubution (Anselin 1992a), written in Gauss (matrix language). Can be applied to data collected on individual zones or areas within a larger geographical area.
  - o Ability to create a spatial weights file, which is a series of weights, assigned to individual observations, indicating their location in relationship to e/o. Two forms of weights:
    - Binary (contiguity matrix that indicates which zones are adjacent to each other)
    - General (distance based matrix that indicates the relative distance of each zone from the others. Typically defined in terms of inverse distance raised to an integer power (eg. $1/d$, $1/d^2$, $1/d^3$); the higher the power of the distance factor, the more "local" the effect.
  - o 4 modules:
    - First allows data to be input and transformed
    - 2nd involves tools for creation of spatial weights input
    - 3rd involves exploratory analysis including descript stats correlations, and principal components. Includes a Join-Count statistic for binary variables and several measures of spatial autocorrelation and descriptive model provides a Local Indicator of

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Spatial Association (LISA) by applying Moran's "I" to individual observations (Anselin 1995)

- 4th module has number of regression routines, with ordinary least squares (OLS) and robust method for estimating OLS using a "jackknife" procedure, and provides diagnostics to examine residuals. Includes tests for spatial autocorrelation, gauging whether spatial dist is affecting either the distribution of the dependent variable or the residual error terms. If no apparent spatial autocorreation, then OLS is valid procedure. If there is spatial autocorrelation, then model that incorporates spatial location must be developed.

- o Most regression packages don't incorporate spatial location and implicitly treat space as if it were random (i.e., part of the residual error term). Spacestat only package that Levine is aware of that explicitly builds location into regression procedure. While one can apply non-spatial statistics to spatial data, the error associated in not considering spatial location is enormous. In effect one is assuming that each observation is independent of all others, which is clearly wrong for spatially affected phenomena.
- o Author provides info on accessing all software described in article

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Levine, N. 1999. Quickguide to CrimeStat. Ned Levine and Associates, Annandale, VA.

- Guide to parallel online help menus in the program.
- Eight program tabs, each with lists of routines, options and parameters
    1. Primary file: point file w/X-Y coordinates.
    2. Secondary file: optional; also point file w/ x-y cords used in comparison with primary file
    3. Reference file: "used for single and dual variable kernel density estimation". Usually though not always a grid overlaying the study area
    4. Measurement Parameters
        a. Area: define area sing units (square miles, square meters…)
        b. Length of street network: total length
        c. Type of measurement – direct (shortest distance between two points) or indirect (distance constrained by grid, called "Manhattan" metric).
    5. Spatial Distribution: provides statistics describing overall distance (1st order spatial stats). 3 routines for describing spatial distance, and 2 routines for describing spatial autocorrelation (intensity variable needed for the latter two routines, weighting variable can also be used) – details on these routines with descriptions are included.

6. Distance Analysis: provides stats about distances between point locations, useful for identifying degree of clustering of points (2nd order analysis). Three routines for describing properties of the distances and two routines that output distance matrices.
    a. Nearest neighbor analysis,
    b. Number of nearest neighbors,
    c. **Linear nearest neighbor analysis
    d. **Number of linear nearest neighbors
    e. **Ripley's K statistic
    f. Distance matrices,
    g. Within file point-to-point: routine outputs distance between each point in primary file to each point in secondary file (can relate to guard rails, intersections, fencing, etc.)
7. Hot spot analysis: identifies groups of incidents clustered together. Second order analysis. 3 stats:
    a. Nearest neighbor hierarchical spatial clustering: groups points together on basis of spatial proximity – user defines significance level associated with a threshold, minimum number of points that are required for each cluster and output size for displaying clusters with ellipses.
    b. K-means clustering routine for partitioning all points into k-groups in which K is a number assigned by the user
    c. Local Moran statistics: applies to the Moran's I statistic to individual points or zones to asses whether particular pts/zones are spatially related to nearby points or zones
8. Interpolation tab: allows estimates of point density using the kernel density smoothing method.

- Chapter 6 Hotspot analysis:
    o Pg 164 overview of types of cluster analyses methods
    1. *Hierarchical* techniques: like inverted tree diagram in which two or more incidents are first grouped on the basis of some criteria (e.g., nearest neighbor). Then these are grouped into second order clusters, which are then grouped into third-order clusters and this process is repeated until either all incidents fall into a single cluster or else the grouping criteria fails.
        - Literature cited: Sneath 1957; McQuitty 1960; Sokal and Sneath 1963; king 1967; Sokal and Michener 1958; Ward 1963; Hartigan 1975
    2. *Partitioning* techniques, or K-means technique, partition the incidents into a specified number of groupings, usually defined by the user. All points are assigned to one (only one) group. Displayed as ellipses.
        - Literature cited: Thorndike 1953; MacQueen 1967; Ball and Hall 1970; Beale 1969
    3. *Density* techniques identify clusters by searching for dense concentrations of incidents (next chapter of book discusses one type of density search algorithm that uses the kernel density method

- Literature cited: Carmichael et al 1968; Gitman and Levine 1970; Cattell and Coulter 1966; Wishart 1969
    4. *Clumping* techniques involve partitioning incidents into groups or clusters but allow overlapping membership
        - Literature cited: Jones and Jackson 1967; Needham 1967; Jardine and Sibson 1968; Cole and Wishart 1970
    5. *Miscellaneous* techniques: other methods less commonly used including techniques applied to zones, not incidents. *Local Moran* (cites Anselin 1995)
    6. Also hybrids of these methods…Block and Green 1994 use a partitioning method with elements of hierarchical grouping

- Optimization Criteria: distinguish techniques applied to space.
    1. Definition of cluster: discrete grouping or continuous variable; whether points must belong to a cluster or can be isolated; whether points can belong to multiple clusters
    2. Choice of variables: whether weighting or intensity values are used to define similarities.
    3. Measurement of similarity and distance: type of geometry used; whether clusters are defined by closeness or not; types of similarity measures used.
    4. Number of clusters: whether there are a fixed or variable number of clusters; whether users can define the number or not.
    5. Scale: whether clusters are defined by small or larger areas; for hierarchical techniques what level of abstraction is considered optimal
    6. Initial selection of cluster locations ('seeds'): whether they are mathematically or user defined; specific rules to define initial seeds
    7. Optimization routines used to adjust initial seeds into final locations whether distance is being minimized or maximized; specific algorithms used to readjust seed locations
    8. Visual display of clusters once extracted: whether drawn by hand or by geometrical object (ellipse); proportion of cases represented in visualization.
- No single solution – different techniques will reveal different groupings and patterns among the groups.
- Chapter goes on to specifically explain Crimestat routines and criteria for 3 techniques –hierarchical clustering based on nearest neighbor analysis; partitioning technique based on K-means algorithm, and zonal technique that identifies zones which are different from their nearby environment, whether they are "peaks" or "troughs"
- Discusses some advantages/limitations for some techniques:
    - Nearest Neighbor Hierarchical Clustering: identify groups of incidents where groups of incidents are spatially closer than would be expected on basis of chance. 4 advantages
        1. Can identify small geographical environments where there are concentrated incidents, useful for specific targeting of

microclimates where incidents are occurring. Sizes of clusters can be adjusted to fit particular groupings of points

2. Can be applied to any entire dataset and need not be applied to smaller geographic areas, easing comparisons between different areas

3. Linkages between several small clusters can be seen through 2nd and higher order clusters – i.e., there are different scales (geographical levels) to the clustering of points and hierarchical clustering can identify these levels

4. Each level may imply different management strategies

▪ Hierarchical clustering limitations

1. Size of grouping area dependent on sample size since lower limit of mean random distance is used as criteria – for distributions with many incidents threshold will be smaller than distribution with fewer incidents, so not consistent definition of hotspot area

2. Arbitrariness due to minimum points rule requiring user to define a meaningful cluster size so two different users may interpret the size of a hotspot differently, also selection of p-value in the students t-distance can allow variability between users. Almost all other clustering techniques have this property too.

3. No theory or rationale behind clusters. Same goes for many other clustering techniques that are empirical groupings with no theory behind them…however if one is looking for a hotspot defined by land use, activities, and targets, the technique provides no insight into why clusters are occurring or why they could be related.

▪ K-means partitioning clustering: data are grouped into k groups defined by user, after specified number of seed locations are defined by user. Routine tries to find best positioning of K centers and assigns each point to the center that is nearest. Assigns points to one and only one cluster, but all points are assigned to cluster, thus no hierarchy (2nd, higher order clusters) in routine. Basically, k-means procedure will divide the data into the number of groups specified by the user.

- Advantages and disadvantages: Choosing too many clusters will lead to defining patterns that don't really exist whereas choosing too few will lead to poor differentiation among areas that are distinctly different. Given the numbers of clusters you choose, the results may or may not relate to actual "hotspots"

▪ Local Moran statistics: aggregate data by zones, applies Moran's I stat to individual zones allowing them to be identified as similar or different to their nearby pattern. Basic concept: LISA local indicator of spatial association, indicator of the extent to which the value of an observation is similar or different from its neighboring observations. Requires two conditions: 1) each observation has a variable value that can be assigned to it in addition to its x/y

coordinates; 2) the neighborhood needs to be defined – could be adjacent zones or all other zones negatively weighted by the distance from the observation zone

- o Some thoughts on Hotspots
  - ▪ 3 advantages to the 3 techniques discussed above
    - • Identifies areas of high or low concentrations of events;
    - • Systematically implements algorithms (though human decisions affect how the algorithms run);
    - • and lastly, these techniques are visual.
  - ▪ Disadvantages:
    - • Choice of parameters in algorithms is subjective…makes this as much an art as science. Greater effect the smaller the sample size.
    - • Applies to volume of incidents, not underlying "risk". It is an implicit density measure, but higher density may be a function of a higher population or risk or both.
    - • One thing to identify a concentration of incidents, but these hotspot methods don't explain why there is a concentration of events there…it could be random, not relate to anything inherent about the location.
    - • Hotspot identification is merely an indication of an underlying problem, but further analyses are required to identify what is contributing to the occurrences in that area.

Levine, N. 2004. CrimeStat III:Distance analysis. Chapter 5 in: A spatial statistics program for the analysis of crime incident locations. Ned Levine & Associates: Houston, Texas, and the National Institute of Justice, Washington, D.C., USA.

- First order properties are global and represent dominant pattern of distribution.
- Second order (or local) properties refer to subregional patterns or neighborhood patterns within overall distribution, and tell about particular environments that may concentrate crime incidents.
- NNI (nearest neighbor index):
  - o Simple to understand, calculate…for AREAS, NOT LINEAR FEATURES.
  - o Basis of many distance statistics, some of which are implemented in CrimeStat.
  - o Compares distances between nearest points and distances that would be expected on basis of chance and is an index that is the ratio of two summary measures.
    - ▪ 1. For each point distance to closest other point (nearest neighbor) is calculated and averaged over all points.
    - ▪ 2. Expected nearest neighbor distance if CSR = the mean random distance.

1. Mean random distance = d(ran) = 0.5 SQRT[A/N] where A is area of region and n is number of points.
- 3. NNI = d(NN)/d(ran) = ratio of observed nearest neighbor distance to mean random distance…..
  2. If observed distance is same as mean random distance, then ratio will be ~1; if observed average distance is smaller than the mean random distance, then the index will be <1 indicating clustering; if observed average distance is greater than the mean random distance, then index >1 indicating dispersion and that points are more widely distributed than would be expected based on chance.
- 4. Testing significance of NNI: Z-test to determine if significant difference between observed and expected. Z= [d(NN)-d(ran)]/[SE of d(ran)]
  3. SE of d(ran)~=SQRT[(4-pi)A/4pi(N-sq)] with A being area of region and n is number of points.
  4. Note: significance test for NNI is not a test for CSR, only a test of if average nearest neighbor distance is significantly different than chance. i.e., test of first order nearest neighbor randomness…there are also 2nd, 3rd, and so forth order distributions that may or may not be significantly different from CSR. All these are K-order effects.
- Edge effects can bias NNI – a point near border of study area may actually have its nearest neighbor on the other side of the border, but program selects another point within the study area as nearest neighbor of border point, which may exaggerate the nearest neighbor distance. No consensus on how to deal with this (cites Cressie 1991 for options) and "this version" of CrimeStat has no correction for edge effects. However, bias will be significantly smaller given datasets with clustering.
- K-order nearest neighbors: beyond nearest neighbor distances, 2nd nearest neighbor, 3rd nearest, etc. In CrimeStat can specify number of nearest neighbor indices to be calculated.
  o Output includes order, starting with 1; mean nearest neighbor distannce for each order (m); expected nearest neighbor distance for each order (m); and NNI for each order.
  o Kth NNI is ratio of observed Kth nearest neighbor distance to the Kth mean random distance.
  o CrimeStat has no test for significance (none has been developed) for kth NNI since orders aren't independent.
  o No restrictions on number of nearest neighbors that can be calculated, but since average distance increases with higher order nearest neighbors, bias from edge effects will increase. Orders no greater than 2.5% of pts should be calculated (cites Cressie 1991 pg 613 for example).
- LINEAR NNI (Lnna): applied to roads, with assumptions that indirect distances are used following network or grid.

- o Theory: cites Hammond and McCullagh (1978).
- o Crimestat calculates average of indirect distances between each point and its nearest neighbor = Ld(NN).
- o Expected linear nearest neighbor distance is Ld(ran)=0.5(L/n-1) where L is total length of road and n is sample size.
- o Linear NNI is = LNNI = [Ld(NN)]/[Ld(ran)]
- o Theoretical standard error for random linear nearest neighbor distance not known
  - ▪ author of Crimestat developed approx SD for observed Ld(NN) = $S_{Ld(NN)}$ =SQRT[Σ(min($d_{i,j}$)-Ld(NN))^2 /N-1] where min($d_{i,j}$) is nnd for point I and Ld(NN) is average linear nearest neighbor distance.
  - ▪ $SE_{Ld(NN)}$=[$S_{Ld(NN)}$]/SQRT[N]
  - ▪ Approx significance test = t = [Ld(NN)-Ld(ran)]/SE of Ld(NN)
  - ▪ Since empirical standard deviation of ld(NN) used instead of theoretical value, t-test used rather than Z-test.
  - ▪ Crimestat output with Lnna routine:
  1) Sample size
  2) Mean linear nearest neighbor distance in meters, feet, miles
  3) Minimum linear dist b/w nearest neighbors
  4) Max " "   "   "   "
  5) Mean linear random distance
  6) Linear nearest neighbor index
  7) SD of linear nearest neighbor distance
  8) SE of linear nearest neighbor distance
  9) Significance test of NNI (t-test)

- • K-order Linear Nearest Neighbors: beyond nearest neighbor distances, 2nd nearest linear neighbor, 3rd nearest, etc. In CrimeStat can specify number of nearest linear neighbor indices to be calculated.
  - o Output includes order, starting with 1; mean linear nearest neighbor distance for each order (m); expected linear nearest neighbor distance for each order (m); and linear NNI for each order.
  - o Kth linear NNI is ratio of observed Kth linear nearest neighbor distance to the Kth linear mean random distance.
  - o Expected linear nearest neighbor distance is Ld(ran)=0.5(L/n-1) where L is total length of road and n is sample size, only adjusting for n_k which occurs as degrees of freedom are lost for each successive order. Index is really the k-order linear nearest neighbor distance relative to the expected linear neighbor distance for the first order – it is not a strict NNI for orders above 1.
  - o (*these are notes from non-linear NNI; not sure if applicable here, too, but there no other notes on these issues in linear NNI section…)….CrimeStat has no test for significance (none has been developed) for kth NNI since orders aren't independent.
  - o (*these are notes from non-linear NNI; not sure if applicable here, too, but there no other notes on these issues in linear NNI section…)….No

restrictions on number of nearest neighbors that can be calculated, but since average distance increases with higher order nearest neighbors, bias from edge effects will increase. Orders no greater than 2.5% of points should be calculated (cites Cressie 1991 pg 613 for example).

- o Example of interpreting results from higher order analyses – if one parameter shows clustering through 4th order, then tending toward more dispersed than random, then may indicate that there are small clusters of points, but that the clusters themselves are relatively dispersed; the more orders analyzed showing clustering, the more overall clustering across the entire study area.
- o Linear k-order nearest neighbor distance difference than non-linear (areal). Index slightly biased as denominator (k-order expected linear neighbor distance) is only approximated. Also, index measures distance *as if* the streets follow a true grid, oriented E/W & N/S, hence may not be realistic for places where streets traverse in diagonal patterns – in these cases, use of indirect distance measurement will produce greater distances than what actually may occur on the street network.

- Ripley's K Statistic (not for linear features—only areas)
  - o Index of non-randomness for different scale values (cites Ripley 1976, 1981; Bailey and Gattrell 1995; Venables and Ripley 1997). "Super-order" NN statistic providing test of randomness for every distance from the smallest up to the size of the study area. Sometimes called *reduced second moment measure* implying that it is meant to measure second-order trends (i.e., local clustering v. general pattern over region); however, also subject to 1st order effects so is not a strictly 2nd order measure.
  - o Consider spatially random dist of n points. Circles of radius, d_s, are drawn around each point, where s is the order of radii from smallest to largest and the number of other points that are found within the circle are counted and then summed over all the points (allowing for duplication), then the expected number of points within that radius are E(number of points within distance d_i) = [N/A]K(d_s), where N is sample size, A is total study area, and K(d_s) is area of a circle defined by d_s. e.g., if area defined by particular radius is ¼ the total study area, and if there is spatially random distribution, on average approximately ¼ of the cases will fall within any one circle (+/- sampling error). More formally, with CSR, expected points within distance d_s is
  - o

$$E(\text{number under CSR}) = [N/A]\,\pi\,d_s^2$$

And if average number of points found within a circle of a particular radius placed over each point is greater than found in above equation (expected), then clustering occurring or if average number of points found within circle of particular radius placed over each point is less than found in above equation (expected), then dispersion.

- K statistic similar to NND because it provides info about average distance b/w points, but more comprehensive than nearest neighbor distance stats for two reasons:
    - Applies to all orders cumulatively, not just a single order
    - Applies to all distances up to the limit of the study area because the count is conducted of successively increasing radii.
- Under unconstrained condition, K is defined as $K(d_s) = [A/N^2] \Sigma_i \Sigma_j I(d_{i,j})$ where $I(d_{i,j})$ is the number of other points, j, found within distance d_s summed over all points, i. So, circle of radius d_s placed over each pt I, then number of other pts ij are counted. Circle is moved to next pt i and process repeated, thus double summation points to the count of all j's for each I, over all I's. when done, radius of circle is increased and process is completed. Typically radii of circle are increased in small increments so there are 50-100 intervals by which the statistic can be counted. In Crimestat, 100 intervals (radii) are used based on $d_s = R/100$ where R is the radius of a circle for whose area is equal to the study area.
- Can graph $K(d_s)$ against d_s to see if there is clustering at certain distances or dispersion at others, but since this plot is non linear (increasing exponentially), then transform into sq-root function $L(d_s) = SQRT[K(d_s)/\pi] - d_s$ ….in practice only the Lstatistic is used even though the name of the statistic is based on the K derivation
- L statistic prone to edge effects i.e., for points located near the boundary of the study area, the number enumerated by any circle for those points will (all other things =) be less than points in the center of the study area because points outside the boundary aren't counted. The > distance between points tested (i.e., the greater the radius of the circle placed over each point), the greater the bias, thus a plot of L v distance will show decline as distance increases.
- Ripley proposed edge adjustments –
    - "guard rail" within study area so points outside the guardrail but inside the study area can be counted for center points (an enumerator) inside the guardrail, but cannot have own circle placed upon them (i.e., only a recipient, can only be j's and not I's). Must be done manually, must identify each point as either an enumerator and recipient or recipient only. Can be problematic if study area boundary not "regular" shape.
    - Another Ripley edge adjustment (Venebles & Ripley 1997) – weighting to account for proportion of circle placed over each point within the study area. Thus $K(d_s) = [A/N^2] \Sigma_i \Sigma_j I(d_{i,j})$ becomes $K(d_s) = [A/N^2] \Sigma_i \Sigma_j W_{ij}^{-1} I(d_{i,j})$ where W_{ij}^{-1} is inverse of proportion of circle of radius d_s placed over each point which is within the total study area; thus if point is near border, it will get greater weight because smaller proportion of circle placed over it will be within the study area. Again, has to be done manually and can be problematic if study area boundary not "regular" shape.

- Crimestat only calculates the unadjusted L and tells users to anticipate the bias by only examining L stat for small distances where bias is smallest (even though you could calculate 100 distance intervals).
  - o Comparison to spatially random distribution…because sampling distribution of L statistic not known, do 100 random distance simulations, then for each simulation the L statistic is calculated for each distance interval, after all simulations have been conducted, highest/lowest L-values are taken for each interval and is called an "envelope". By comparing distribution of L to random envelope, one can assess if observed is different from chance.
    - Note: since no formal test of significance, comparison with envelope only approximate confidence about whether distribution differs from chance or not i.e. one can't say likelihood of obtaining this result by chance is less than e.g., 5%.

Spooner, P.G., I.D. Lunt, A. Okabe and S. Shiode. 2004. Spatial analysis of roadside *Acacia* populations on a road network using the network K-function. Landscape Ecology 19:491-499.

- Ripley's K-function (Ripley 1976, 1991) not appropriate for point patterns on road networks since k-function assumes infinite homogeneous environment for calculating Euclidean distances.
- Network k-function for univariate analyses and network cross k-function for bivariate analyses more appropriate
- Used these methods to confirm significant clustering of Acacia populations at various scales and spatial patterns
- K-function been used to study spatial patterns of mapped point data in plant ecology (cites a list…)
- K-function uses all point to point distances not just nearest neighbor distances
- When k-function used to for point patterns constrained by linear road networks, can overdetect clustering patterns possibly leading to Type 1 errors
- Cites Forman 1999 ICOET article says lack of spatial tools to analyze point patterns on road networks.
- Credits Okabe and Yamada 2001 ("The k-function method on a network and its computational implementation. Geographical analysis 33:271-290) with developing k-function analysis of point patterns on a network.
- Refers to k-function to "reduced second moment measure" to measure two dimensional distribution pattern on infinite homogeneous plane where circle of radius t centered on each point and number of neighboring points within circle are counted. Can vary radius t scale, deviation of observed from expected number of points plotted against t…null hypothesis for k-function is complete spatial randomness (CSR) and if observed function deviates from a randomly generated (Poisson) point process, the null is rejected

- univariate network k-function similar process but calculates the shortest path distance from each point to all other points on a finite connected planar network, assumption of binomial point process based on hypothesis that points p (the set of points assumed on network) are uniformly an independently distributed over finite road network, thus if hypothesis rejected, points are spatially interacting and may form non-uniform patterns.
- 100 Montecarlo simulations used to construct confidence "envelope" based on max and min values from an equivalent number of random coordinates for k(t) compared to k-hat (t) or observed. Any values of k-hat (t) that lie outside confidence envelope were considered significant deviation from CSR. If k-hat(t) > k(t), then points p are clustered; if k-hat(t) < k(t), then points p are tending toward regularity. Edge effects are taken into account with distance computations so no need for edge adjustment factor (Okabe & Yamada 2001)
- Bivariate network-k function, two different kinds of points A&B are anlysed on network, with hypothesis of spatial interaction between different types of points. Statistical test for bivariate analysis similar to univariate network k-function but present version of SANET used for network cross k-function analyses does not construct a confidence envelope, but can be theoretically obtained from the binomial distribution approximated by normal distribution for large number of points. To check for statistically significance of observed from CSR, approx of 95% CI constructed using standard deviation of normal distance, and max/min values of +/-1.65*SD using one-sided tests. If observed > expected and outside CI, then points A&B are significantly "attracted" if observed < expected and outside CI, then points A&B are significantly repelled.
- "Spatial point patterns were analyzed on a road network shape-file using SANET Version 1.0 – 021125 (Okabe et al 2002 –http://okabe.t.u-tokyo.ac.jp/okabelab/atsu/sanet/sanet-index.html), an ESRI Arcmap extension. First preprocessed all polylines to make sure properly connected to e/o. Sanet used first to calculate distances between all notes on road network then used to assign points to the nearest point on the road network. Network k and cross k function analyses were performed by Sanet and output data were exported to excel to aggregate data, calculate confidence intervals (for x-k-function analyses) and produce graphs."
- Univariate addresses clustered vs regular distributions; bivariate addresses if two types of sets of points are attracted or repulsed from e/o.
- Combo of using graphical Kernel (for visual) and network k-function was helpful, but must be realized that kernel estimations do not compensate for spatial differences I road networks and their effect on point patterns observed.

Final paragraph: possible applications of network k function include animal movement patterns from survey and traffic mortality, envision network k-function becoming standard GIS application on networks.

Appendix F: Distance Sampling

Buckland et al.[40] suggest that the modeling process for the analysis of line or point transect data can be visualized as having two steps. The first involves selecting a key function as the starting point (Figure 38), starting with the uniform or half-normal. The uniform model has no parameters,[40] while the half-normal has one unknown parameter that has to be estimated from the data. The second step is to adjust the key function (above) with a series expansion. Buckland et al.[40] suggest using: a) the cosine series, b) simple polynomials, or c) the Hermite polynomials. All three are linear in their parameters.[40] Given below in Figure 39 are the key function and the series expansion.
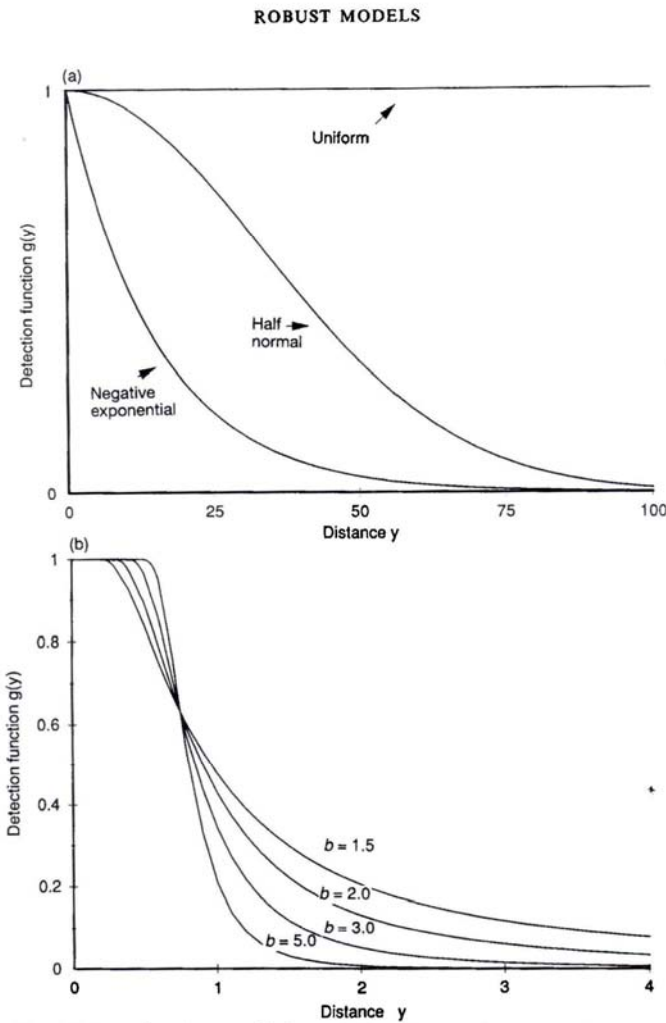

Figure 38: Functions useful in modeling distance data: a) uniform, half-normal, and negative exponential, and b) hazard-rate model for four different values of the shape parameter *b*. From Buckland et al. 1993

Key function	Series expansion
Uniform, $1/w$	Cosine, $\sum_{j=1}^{m} a_j \cos\left(\dfrac{j\pi y}{w}\right)$
Uniform, $1/w$	Simple polynomial, $\sum_{j=1}^{m} a_j \left(\dfrac{y}{w}\right)^{2j}$
Half-normal, $\exp(-y^2/2\sigma^2)$	Cosine, $\sum_{j=2}^{m} a_j \cos\left(\dfrac{j\pi y}{w}\right)$
Half-normal, $\exp(-y^2/2\sigma^2)$	Hermite polynomial, $\sum_{j=2}^{m} a_j H_{2j}(y_s)$ where $y_s = y/\sigma$
Hazard-rate, $1 - \exp(-(y/\sigma)^{-b})$	Cosine, $\sum_{j=2}^{m} a_j \cos\left(\dfrac{j\pi y}{w}\right)$
Hazard-rate, $1 - \exp(-(y/\sigma)^{-b})$	Simple polynomial, $\sum_{j=2}^{m} a_j \left(\dfrac{y}{w}\right)^{2j}$

Figure 39: From Buckland et al. 1993

Appendix G: Allometric Scaling

North American terrestrial mammals scaling distances grouped by linear [√ HR (mi)] movement domains (gray shaded column), using Ward's linkage method with a Euclidean distance measure to produce a hierarchical monothetic agglomerative clustering.[162]

Table 47: North American terrestrial mammals scaling distances

common name (Genus species)	HR[1] (ha)	HR (mi[2])	√ HR (mi)	MED DD[2] (mi)
Clustering Classes				
> 11 miles[3]				
wolverine (Gulo gulo)	150000.00	579.1500	24.07	168.46
< 11 ≥ 10.71				
mountain lion (Felis concolor)	29733.33	114.8004	10.71	75.00
< 10.71 > 7.15 miles				
fisher (Martes pennanti)	20342.49	78.5424	8.86	62.04
wolf (Canis lupus)	20276.88	78.2890	8.85	61.94
< 7.15 miles ≥ 3.05 miles				
grizzly bear (Ursus arctos)	9283.13	35.8422	5.99	41.91
coyote (Canis latrans)	7597.57	29.3342	5.42	37.91
black bear (Ursus americana)	2413.09	9.3169	3.05	21.37
< 3.03 ≥ 1.07 miles				
arctic fox (Alopex lagopus)	2080.00	8.0309	2.83	19.84
lynx (Lynx canadensis)[4]	1852.40	7.1521	2.67	18.72
bighorn sheep (Ovis Canadensis)[4]	1433.40	5.5344	2.35	16.47
elk (Cervus elaphus)[4]	1292.54	4.9905	2.23	15.64
moose (Alces alces)	1215.00	4.6911	2.17	15.16
pronghorn antelope (Antilocapra americana)	1060.47	4.0945	2.02	14.16
badger (Taxidea taxus)	849.87	3.2813	1.81	12.68
swift fox (Vulpes velox)	793.02	3.0619	1.75	12.25
antelope jackrabbit (Lepus alleni)	642.82	2.4819	1.58	11.03
prairie red fox (Vulpes vulpes fulva/regalis)	409.76	1.5821	1.26	8.80
red fox (Vulpes vulpes)	387.34	1.4955	1.22	8.56
bobcat (Lynx rufus)	320.82	1.2387	1.11	7.79
striped skunk (Mephitis mephitis)	294.67	1.1377	1.07	7.47
< 1.07 ≥ 0.16 miles				
mule deer (Odocoileus hemionus hemionus)	285.27	1.1014	1.05	7.35
American marten (Martes americana)	209.31	0.8081	0.90	6.29
white-tailed deer (Odocoileus virginianus)	196.06	0.7570	0.87	6.09
black-tailed jackrabbit (Lepus californicus)	145.55	0.5620	0.75	5.25
collared peccary (Pecari tajacu)	135.21	0.5220	0.72	5.06
gray fox (Urocyon cinereoargenteus)	122.00	0.4710	0.69	4.80
long-tailed weasel (Mustela frenata)	111.29	0.4297	0.66	4.59
raccoon (Procyon lotor)	113.73	0.4391	0.66	4.64
ringtail cat (Bassariscus astutus)	87.75	0.3388	0.58	4.07
California black-tailed deer (Odocoileus hemionus californicus)	79.44	0.3067	0.55	3.88
black-tailed deer (Odocoileus hemionus columbianus)	58.85	0.2272	0.48	3.34
opossum (Didelphis marsupialis)	59.88	0.2312	0.48	3.37

common name (Genus species)	HR[1] (ha)	HR (mi²)	√ HR (mi)	MED DD[2] (mi)
coati (Nasua narica)	55.00	0.2124	0.46	3.23
cotton rat (Sigmodon hispidus)	44.50	0.1718	0.41	2.90
short-tailed weasel, ermine (Mustela erminea)	20.64	0.0797	0.28	1.98
American mink (Mustela vison)	14.10	0.0544	0.23	1.63
porcupine (Erithizon dorsatum)	11.29	0.0436	0.21	1.46
Mountain western American Chipmunk (Tamias quadrivittatus)	6.73	0.0260	0.16	1.13
least weasel (Mustela nivalis)	6.75	0.0261	0.16	1.13
< 0.16 miles				
snowshoe hare (Lepus americanus)	5.93	0.0229	0.15	1.06
flying squirrel (Glaucomys volans/sabrinus)	4.14	0.0160	0.13	0.89
west central U.S. chipmunk (Tamias umbrinus)	4.55	0.0176	0.13	0.93
grasshopper mouse (Onychomys leucogaster)	3.62	0.0140	0.12	0.83
desert cottontail (Sylvilagus audubonii)	3.18	0.0123	0.11	0.78
western and Siberian American chipmunk (Tamias minimus)	2.10	0.0081	0.09	0.63
swamp rabbit (Sylvilagus aquaticus)	2.12	0.0082	0.09	0.63
eastern cottontail (Sylvilagus floridanus)	1.62	0.0063	0.08	0.55
pine squirrel (Tamiasciurus douglasii)	1.10	0.0042	0.07	0.46
red squirrel (Tamiasciurus hudsonicus)	1.10	0.0042	0.07	0.46
kangaroo rat (Dipodomys ordii)	1.29	0.0050	0.07	0.49
creeping vole, Oregon vole (Microtus oregoni)	0.81	0.0031	0.06	0.39
white-footed deer mouse (Peromyscus maniculatus gracilis)	0.81	0.0031	0.06	0.39
gray squirrel (Sciurus carolinensis)	0.95	0.0037	0.06	0.42
pine vole (Microtus pinetorum)[4]	0.58	0.0022	0.05	0.33
13 lined ground squirrel (Spermophilus tridecemlineatus)	0.66	0.0025	0.05	0.35
pika (Ochotona princes)	0.35	0.0014	0.04	0.26
American shrew mole (Neurotrichus gibbsii)	0.41	0.0016	0.04	0.28
short-tailed shrew (Blarina brevicauda)	0.43	0.0017	0.04	0.29
New England Cottontail (Sylvilagus transitionalis)	0.46	0.0018	0.04	0.30
collared lemming (Dicrostonyx groenlandicus)	0.20	0.0008	0.03	0.19
red-backed vole (Clethrionomys gapperi)	0.25	0.0010	0.03	0.22
brush rabbit (Sylvilagus bachmani)	0.28	0.0011	0.03	0.23
western gray squirrel (Sciurus griseus)	0.30	0.0012	0.03	3.24
yellow-bellied marmot (Marmota flaviventris)	0.31	0.0012	0.03	0.24
pocket mouse (Perognathus longimembris)	0.31	0.0012	0.03	0.24
western American mole (Scapanus townsendii)	0.10	0.0004	0.02	0.14
long-tailed shrew (Sorex vagrans)	0.11	0.0004	0.02	0.14
prairie vole (Microtus ochrogaster)	0.11	0.0004	0.02	0.14
Eastern American chipmunk (Tamias striatus)	0.11	0.0004	0.02	0.14
meadow vole (Microtus pennsylvanicus)	0.12	0.0005	0.02	0.15
tundra vole (Microtus oeconomus)	0.16	0.0006	0.02	0.17
northern pocket gopher (Thomomys talpoides)	0.02	0.0001	0.01	0.06
bog lemming (Synaptomys cooperi)	0.05	0.0002	0.01	0.09

[1]HR = Home Range
[2]Med DD = Median Dispersal Distance 7√HR)
[3]These are allometric distance domains established by the clustering technique
[4]Corrected scientific names to currently accepted usage