DATA ISSUES IN DESCRIBING ROAD MORTALITY HOTSPOTS AND CREATING PREDICTIVE MODELS

John A. BISSONETTE. USGS Utah Cooperative Fish and Wildlife Research Unit College of Natural Resources Utah State University Logan UT 84322-5290 USA. 435-797-2511. john.bissonette@cc.usu.edu

[1]**Christine KASSAR.** USGS Utah Cooperative Fish and Wildlife Research Unit College of Natural Resources Utah State University Logan UT 84322-5290 USA. 435-797-3598. chaka@cc.usu.edu

Date of revision: 06-26-06

Corresponding author: J. A. Bissonette, USGS Utah Cooperative Fish and Wildlife Research Unit, Department of Wildland Resources, College of Natural Resources Utah State University Logan UT 84322-5290 USA. john.bissonette@usu.edu

Word Count (all figure captions, tables ad references): 7978

[1] Current address: Center for Biological Diversity, Tucson, AZ

Abstract: Vehicle speed and traffic volume often are cited as important determinants of the number of animal-vehicle collisions (AVCs), but consensus seems elusive. To understand the effects of posted speed limit and annual average daily traffic flow (AADT) and to try to make sense of the conflicting reports in the literature on wildlife-vehicle collisions and kill hotspots, we conducted a 2-part investigation that included: 1) an extensive literature review; and 2) a case study involving an analysis of the effects of traffic volume and posted speed an animal-vehicle crashes in Utah. Trends found in the literature varied, and the results from our case study showed no relationship between traffic volume and/or posted speed limit and the number of wildlife-vehicle collisions that occurred. General reasons include problems with the scale resolution and extent of how data is collected, as well as data quality itself. If the objective is to define hotspots of road kill for mitigation action, then analyses that use existing data accurate to the mile marker can aid in the prioritization of mitigation measures and will have quick beneficial effects on restoring landscape permeability. However, developing reliable and accurate predictive models of animal-vehicle crashes using explanatory environmental and roadway variables requires that: (1) road kill data is spatially explicit, (2) data regarding explanatory variables and road kill are recorded at appropriate scale extents and resolutions, (3) data are recorded accurately and completely, (4) the model considers not only road geometrics but also environmental variables, and (5) the model considers both driver behavior and animal behavior. We discuss the problems with describing wildlife-vehicle hotspots and identify ways to address these issues.

Keywords*:* connectivity; mitigation; road ecology; road geometrics; predictive models; scaling; wildlife-vehicle collisions

Introduction

Roads have a significant impact on the natural environment (Trombulak and Frissell 2000) including the health of ecosystems (Forman and Alexander 1998), the diversity of communities (Forman 1998), and the abundance of species in an area (Groot Bruinderink and Hazebroek 1996). Perhaps the most obvious direct effect of these impacts is evidenced by animal mortality on the road (Bissonette 2002). Scientists have attempted to explain wildlife road mortality by identifying certain explanatory environmental and road variables that correlate with areas of a high concentration of collisions, i.e., hotspots. Road characteristics, usually referred to collectively as road geometrics, including vehicle traffic volume and speed limit, have been reported to directly influence rates of animal-vehicle collisions (Forman and Alexander 1998). Depending on the species and area, some studies have suggested that vehicle volume is highly correlated with animal mortality (Inbar and Mayer 1999), while others implicate speed as the major cause of collisions (Case 1978; Staines 2001). There is, however, ambiguity in published results. For example, McCaffrey (1973) argued that local average daily traffic flow was too variable to allow for conclusions. Allen and McCullough (1976) found that traffic volume varied throughout different times of the day and was not closely correlated with deer-vehicle collisions; however, when deer activity increased during dusk and dawn periods, traffic volume explained 85% of deer-vehicle collisions. They found a low correlation between *seasonal* traffic volume and deer-vehicle collisions. Romin & Bissonette (1996) evaluated mule deer (*Odocoileus hemionus*) mortality on 3 highways and found that areas with more kills also had greater vehicle volumes and speed. In their discussion, however, they emphasized the impact that traffic volume had on overall deer kills; vehicle speeds were not as strongly or consistently correlated. Rolley and Lehman (1992) did not find a positive correlation between traffic volume and kills; rather they implicated speed as a major cause of mortality, but suggested difficulties in determining the relative importance of speed in relation to other variables on road mortality of raccoons. Gunther et al. (1998) concluded that the actual speed of vehicles, rather than the posted speed limit was more closely correlated with wildlife-vehicle collisions. Bashore et al. (1985) evaluated posted speed limit at kill sites and found that it was negatively correlated with deer kill probability; they suggest that posted speed may have little relationship to actual vehicle speeds and that deer may cross less frequently at spots where vehicles move more quickly. This brief summary, with its attendant variation in the conclusions drawn and in the strength of correlations found, suggested to us that a closer examination was needed. It seemed to us that, at a minimum, attention to the scale resolution and extent with which the explanatory variables were collected may not have been considered, thus possibly resulting in different interpretations of the data. To understand the effects of posted speed limit and annual average daily traffic flow (AADT) and to try to make sense of the conflicting reports in the literature on wildlife-vehicle collisions, we conducted a 2-part study. The first involved an extensive literature review to determine how consistent study results were regarding the effects of traffic volume and speed. Second, we conducted a case study analysis of traffic volume and posted speed limit correlations on 4 state routes in Utah, USA. to understand the nature of the problem

Methods

Literature Review

To determine the degree of consistency among findings, we conducted an extensive review of the literature on wildlife-vehicle collisions and factors that may contribute to them. We were especially interested in whether conclusions were based on data analysis. The literature included a random sample of those articles cited most consistently. To ensure that we had a representative sample, we conducted a BIOSIS computer search and categorized the results by authors who stated conclusions based on their own data or on other literature.

Case Study Route Analysis

Study area description

Utah is diverse, consisting of mountainous, desert, rangeland, agricultural, wetland and urban regions. This varied terrain is transected by ~9500 km (~5,900 miles) of state routes and ~ 56, 327 km (~35,000 miles) of city and county roads that are being used by a growing number of drivers. The case study area consisted of 4 state routes within Utah that had a significant amount of collisions (6,198 or 25.6% of total collisions). The state routes chosen from the 248 total routes in Utah were: 40, 89, 189 and 91.

Data description

The Utah Department of Transportation (UDOT) maintains a database of information on vehicle crashes reported within Utah. We accessed data from 1992 to 2002. The data originates from accident forms filled out by law enforcement officers (Utah Department of Public Safety) at the scene of animal-vehicle crashes and are provided to UDOT. The database contains information for all types of collisions, including those that involved a motor vehicle colliding with a wild animal. A wildlife-vehicle collision was included in the database *only* if the vehicle damage due to the crash exceeded $1,000, and/or personal injury or death resulted. Collisions that occurred as a result of swerving to miss an animal, those that resulted in less than $1,000 in damage and/or those with no human injuries were not included in the database. Because of these constraints, animal-vehicle collisions are underreported, and the number of collisions reported here should be considered minimum estimates (Jahn 1959; Groot Bruinderink and Hazebroek 1996). Almost all animal-vehicle crashes in Utah involved mule deer; less than 1% involved moose *Alces alces* and elk *Cervus elaphus*.

The collision data used for this paper came directly from the UDOT database containing information for each reported wildlife-vehicle collision occurring on all 248 routes in Utah from 1992-2002. For each of the 24, 210 wildlife-vehicle collision records within the data set, there were corresponding variables, including: route number, milepost, date, time, locality, alignment and posted speed limit. The UDOT collision database consists of 2 main sections: ‘Accident’ and ‘Traffic.’ The ‘Traffic’ section contains the Annual Average Daily Traffic (AADT) flow information (traffic volume) for each route by year. We searched the ‘Traffic’ section for each route individually from 1992-2002 and compiled this into a spreadsheet which was then imported into SAS 9.1.3.

We identified segments of road that had 11 or more collisions per mile over the 11 year period 1992-2002, i.e., at least one accident per year. This process was repeated for each of the 248 state routes that exist in Utah. For this analysis, we chose 4 sample routes: 40, 89, 91, and 189 because they had a significant number (6,198; 25.6%) of wildlife-vehicle collisions.

Traffic volume data

In Utah, traffic volume data is recorded by hose-like sensors placed on sections of each highway for a 48 hour time period. The sensors recorded the days of the week, the month, and the functional class of the route, e.g.; interstate, collector, other. Full time, inductive loop-based counters throughout the state provide 365 days of data that are used to generate growth factors for each functional class, that are then used to estimate changes in volume and to adjust the 48-hour counts for the time of year that the count was taken. Sections are counted on a rotating 3 year cycle; for the second and third years the AADT is based on a growth factor. To yield an AADT for a specific section of road, conversion growth factors for the day of the week and month are applied to the value recorded within the 48-hour period. As development occurs, the location where data are collected may differ from year to year. An entire route may not be counted on the same day and individual sections may not be recorded on the same days each year. Presumably, functional class conversion factors adjust the 48-hour reading to reflect correct AADT volumes. Counters are placed on the landscape according to parameters that affect road design (e.g., number of lanes or intersections). Thus, AADT is collected from road segments with unequal lengths. These segments are not uniform in length among or within routes. In the data set, AADT varied the most along a route because it corresponded to individual segments of unequal length. Because this variable had the most variation in length, we used these sections of road as the defining sections for our model. Using SAS, we extracted the data for each route from the larger dataset and created 4 separate traffic volume datasets (Fig. 1, STEP 1). For each route, we assigned a section number to each volume-defined segment of road (Fig. 1, STEP 2). We took the mean volume of all the years for each segment of road and based on milepost, assigned it to its corresponding section (Fig.1, STEP 3). We used the mean value for volume because it evenly weights data from each of the 11 years and because the number of wildlife-vehicle collisions did not vary significantly from year to year (Bissonette and Kassar, unpublished data). Then, we assigned each animal-vehicle crash that occurred on that route into a section based on its milepost (Fig.1, STEP 4). We then tallied the number of records in each section and calculated the *event density* (number of collisions per segment mile) for each of these sections (Fig. 1, STEP 5). By standardizing the collision data into event density, we were able to determine if a correlation exists between AADT and the number of collisions across road segments of unequal lengths.

Posted speed limit (mph) data

In the original dataset the posted speed limit (mph), as well as an actual estimated vehicle speed were assigned for each collision. We calculated the median posted speed for collisions occurring in each section and compared it to the event density to determine the nature of the relationship. The speed limit data were variable; values reported ranged from 0 to 75 mph. Because there were no road segments with a posted speed limit of 0, we removed these collisions from our analysis. Compared to the mean, the median is less affected by high or low measurements and is thus, “a resistant statistic" (Zar 1999). In addition, the median can still be calculated if data are not accurate for all members of the sample (Zar 1999). Because we questioned the reliability of the data and because the reported speed limit for a route did change frequently, we chose the median value to reflect the most common condition drivers would face and to prevent outliers from skewing the results. By doing this we were purposely trying to maximize the possibility of a significant relationship; in other words, this was a best possible case scenario for these data.

Statistical analysis

We used SAS 9.1.3 to perform a multiple regression and evaluate how the independent variables (AADT and posted speed limit) related to the dependent variable (the number of collisions). We standardized the number of collisions by calculating event density because each of the volume-defined sections was of different length. We compared mean volume and median posted speed with event density to show the (putative) relationship between the accident rate and these 2 road geometric variables.

Results

Literature review

We reviewed 40 articles from the literature on animal-vehicle collisions for findings regarding correlations between wildlife-vehicle collisions and posted speed limit, vehicle speed and traffic volume (Table 1A,1B). Posted speed limit was addressed in 7 of 40 papers (17.5%). Of the 32 authors who drew conclusions from data, 4 found a significant correlation, 2 no significant correlation, and 26 did not consider speed limit in their analysis (Table 1A). Of the 8 authors who used literature to make their assertions, 1 cited a correlation while 7 did not consider the impacts of posted speed limit. Overall, 5 cited a correlation (12.5%), 2 found no correlation (5%) and 33 did not address speed limit in their research (82.5%).

Vehicle speed was considered more often than posted speed (n=21, 52.5%). Of the 32 authors who drew conclusions from data (Table 1A), 6 authors (18.8%) found a significant correlation, 2 (6.3%) found no significant correlation, 6 (18.8%) cited that vehicle speed had an impact, but did not cite statistics to support this claim while 18 authors (56.3%) did not address the impacts of vehicle speed. Of the 8 authors who used literature to make their assertions (Table 1B), 6 (75%) reported correlations; 1 author (12.5%) stated that correlations vary depending on species and 1 did not consider vehicle speed in his analysis. Considering all 40 papers, 18 (45%) reported a correlation between vehicle speed and wildlife-vehicle collisions, 2 (5%) found no correlation, 1 (2.5%) argued that correlations varied and 19 (47.5%) did not consider vehicle speed.

Traffic volume was considered more often than posted speed limit or vehicle speed with 31 of the 40 papers (77.5%) drawing a conclusion regarding this variable. Of the 32 authors who drew conclusions from data (Table 1A), 9 (22.5%) reported a significant correlation, 4 (10%) found no significant correlation, 3 (7.5%) found a negative correlation, 6 (15%) reported that traffic volume did have an impact but did not cite statistics, and 1 (2.5%) cited changing traffic volume as a source of bias in his study. Nine of these authors (22.5%) did not address traffic volume in their research (Tables 1A,B). Of the 8 authors who used literature to make their assertions (Table 1B) 7 authors (87.5%) stated that traffic volume has an impact, while 1 author

(12.5%) reported that no conclusions could be drawn because the effects of traffic volume were ambiguous. In summary, 22 reported a correlation (55%), 4 found no correlation (10%), 3 found a negative correlation (7.5%), and 9 authors did not include traffic volume in their analysis of explanatory variables (22.5%). Two authors did not fall into these categories because one claimed the relationship is too ambiguous (2.5%) and another cited traffic volume as a source of bias (2.5%).

Individual routes- Utah case study

In none of the four routes we analyzed were multiple regressions between volume and speed as explanatory variables and number of animal-vehicles collisions (standardized event density) as the response variable significant. For routes 40, 89, 91, and 189, the adjusted regression coefficients (adj. R^2) were = 0.0494, 0.0231, 0.0148, and -0.0376, respectively. Relevant data are given in Table 2. Typical results of the analysis are given for Route 91 in Fig. 2. We visually compared event density, mean volume, and median posted speed with the AADT volume-defined sections to examine how these variables were distributed across the route. It is clear from Fig. 2A that these variables change differently along volume-defined road segments. Additionally, results of correlations between median posted speed and event density (Fig 2B) and mean traffic volume and event density (Fig 2C) in no way conform to the putative expected relationship (45^0 isoclines).

Discussion

Although the trends in the literature varied, within a database of over 24,000 records, ceteris paribus, one might expect to see definite patterns in terms of the factors impacting road mortality hotspots, i.e., between traffic volume and/or posted speed limit and wildlife-vehicle collisions. As the values of these road variables increase, the expectation is that the number of wildlife-vehicle events should also increase. However, our case study results did not support these expectations. At least 4 explanations are possible. First, there may be no causal relationship between posted speed limit and/or traffic volume and wildlife-vehicle collisions. Second, the nature of the data, i.e., how the data are collected, its quality, and scale extent and resolution data problems may confound the relationship and preclude any meaningful analysis. Third, a relationship may exist, but speed and volume by themselves may explain only a small part of the variance of the relationship involved in wildlife-vehicle collisions such that the relationship is not apparent in our analysis. Fourth, some combination of reasons 2 and 3 may exist. The following discussion explores these alternative hypotheses.

Lack of a causal relationship?

It is unlikely that the potential causal explanations we discuss are independent of one another. Indeed this is our point 4. If there is no causal relationship between event density vs. posted speed and/or traffic volume, as our results seem to show, then little more need be said. However, in order to determine this conclusively, it is necessary to explore issues related to problems with the data. If the data are accurate, and collected in a manner that allows comparison, and the result is still no relationship, then the conclusion of no effect may be warranted. Additionally, selection of these two variables (speed and traffic volume) as explanatory may be problematic and give poor results if other variables account for most of the variance. As we discuss below, if a relationship is present, it is most probably confounded by data problems.

Data Problems

We perceive three different problems with these types of data. The first involves the very nature of the data, including how it is assigned and collected, the second involves scaling issues, while the third involves data quality. We discuss below how these 3 problems are manifested in our data.

Problems with how data are collected

Problems with the nature of data may arise from the way data are assigned or collected. Such problems do not suggest that the data are poor. Rather, such difficulties may arise because data that was collected for one purpose (viz. record-keeping) are being used for another (viz., analysis of wildlife-vehicle collisions. The nature of how posted speed is assigned to road segments may be inimical to its use in analyzing its relationship to animal-vehicle collisions. For example**,** posted speed limits may change *within* a mile segment and on the same segments of road from year to year (Fig 3). This data issue is inherent in how roads are designed (curves, blind spots, straight stretches of road) and how they change over time (i.e., construction, other development), making it difficult to use posted speed limit data to describe causal relationships within a hotspot or to make predictions regarding the effects of posted speed limits on wildlife-vehicle collisions. Additionally, because drivers may not observe the posted speed limit, it may not be a reliable surrogate for actual vehicle speed; actual vehicle speed may impact wildlife-vehicle collisions more than posted speed limit. Perhaps actual vehicle speed would be a better explanatory variable. For each collision that we analyzed, there was an estimated vehicle speed. However, we did not use these data because they varied greatly, calling into question collection methods and reliability. Using electronic detectors to record vehicle speed in areas where animal vehicle crashes are more probable (viz., hotspots) may provide more accurate data (Gunther et al. 1998).

Likewise, vehicle volume data are collected in a manner so as to preclude its use to evaluate its effect on animal vehicle collisions. For example UDOT uses sensors to collect traffic volume data on specific sections of road for 48 hours each year; from this value estimates are made based on certain road characteristics to determine an annual average daily traffic flow (AADT). However, traffic volume is continually changing, thus to draw conclusions regarding its impact we need data that can reflect these temporal changes and their effect on wildlife-vehicle collisions. To the extent that other DOTs collect speed and volume data similarly, the problems are manifest. Allen and McCullough (1976) explored how changes in traffic volume due to time of day, day of the week and season affected the number of collisions. They found that traffic volume was an important explanatory variable because deer-vehicle collision patterns shifted based on hour, day, and season.

Spatially, different locations along a road will have varying traffic volumes. The sensors that UDOT and presumably other agencies or ministries use to collect data are placed at locations along a route based on road design. Sections are defined by parameters that affect the road design, i.e., number of lanes or intersection with other state or federal routes. Thus, volume data do not reflect changes in the adjacent landscape, does not correspond to mile markers, and does not correspond to a specific wildlife-vehicle collision (Fig 3.). This variation in volume segment length measurement makes it difficult to use this kind of data in any comparison with wildlife collision data.

Scaling Issues

Problems with the nature of the data also become evident when we consider the scale resolution and extent at which data are collected and recorded. The database provides road variables in relation to a single collision, but we are attempting to describe a 'hotspot,' or a group of collisions spanning 1 mile or multiple consecutive miles. If the variable of interest (i.e., posted speed limit, traffic volume, road alignment, adjacent vegetative cover, etc.) changes within the distance of the hotspot, then determining which variable value to use becomes problematic. In our analysis, we used three variables, each recorded at different spatial and temporal scale resolutions and extents: 1) collisions are recorded to the nearest milepost, hour and minute; 2) posted speed limit is recorded for each collision but may vary within a hotspot, and 3) traffic volume (AADT) is recorded for segments of road of varying lengths and also may vary within a hotspot (Fig. 3). Thus, we argue that variation in scale resolution and extent of these variables is great enough that they may not be informative in describing hotspots. Inbar and Mayer (1999) argue that ambiguous results regarding correlations between traffic volume and wildlife-vehicle collisions may exist because of the scale resolution of traffic-volume data. They state that the traffic volume that animals actually encounter on the landscape may differ from that represented by traffic volume data recorded annually or monthly. Attempts to predict a pattern based on posted speed and volume is difficult because data used to do so are often recorded at differing spatial scales. Given the recent emphasis on the importance of spatial explicitness, the problem of varying scales might be solved if wildlife-vehicle crash data were recorded at finer scale resolutions than to the specific mile marker, the level of accuracy normally available in crash databases. Mansfield and Miller (1978) found poor correlations because the speed and traffic volume data available to them was not precise enough to be applicable at a small enough (0.01 mile) resolution. We argue that acceptably accurate predictions could be made if data were recorded in a more spatially explicit manner. Ideally, data regarding the posted speed limit, the traffic volume and other explanatory variables should be recorded at the AVC location. Additionally, consideration of collisions at both the landscape extent and the locally may help to create models with greater predictive power. Malo et al. (2004) modeled collisions by road section and by crash point, allowing for the implementation of both broad-scale and specific mitigation measures. This level of data accuracy will be expensive and time consuming but may be justified for specific purposes.

Data Quality Issues

Data quality issues call into question the accuracy and reliability of recorded values. The posted speed limit value set included missing values, inaccurate zero values (i.e., posted speed limit = 0 mph) and records with more than one value for one field (i.e., 2 different mile markers for one accident). Possible explanations for such inconsistencies include: errors made in recording data at the collision site, errors in entering the data into the database, variation in the road (i.e., curves and construction) leading to changes in posted speed limit within a mile or from year to year, and a lack of data quality checks. We fixed as many of these issues as possible by returning to the original database and cross checking collision records. The vehicle volume data set did not appear to have data quality issues, except for those stemming from data collection procedures.

Are Road Geometrics Sufficient? The role of animal exposure

Posted speed limit and traffic volume may explain only a small part of the variance of the relationship involved in wildlife-vehicle collisions. A model that completely represents relationships between explanatory variables and wildlife-vehicle collisions will consider a range of road and environmental variables. In addition to posted speed limit and traffic volume, other road variables have been evaluated for causality in wildlife road mortality. Romin (1994) found that areas with different road alignments (i.e., straight, hilly, and curved) had no significant impact on collision numbers. However, she suggested that other aspects of highways, including number of lanes and passing opportunities may have contributed to higher road kill levels. Arnold (1978) analyzed the types of roads where accidents occurred in Michigan and found that the most hazardous roads were local roads, accounting for 51.8% of the accidents; 7% occurred on interstates, and 28% on two-lane state highways.

In addition to the road itself, the composition and configuration of the landscape adjacent to a road certainly is expected to have an impact on the number of wildlife-vehicle collisions that occur. Studies show that the proximity of habitat cover and wildlife movement corridors to the road side greatly influence road-kill rates (Forman et al. 2003). This is because the surrounding landscape influences movement patterns of species in relation to roads. When considered in the framework of animal behavior, topographic and vegetative features in proximity to a road influence habitat use and movement patterns, hence animal exposure, contributing to wildlife mortality (Morrison et al. 1992, Clevenger et al. 2001, Clevenger et al. 2002, Clevenger and Waltho 2005).

Landscape spatial pattern plays a role in shaping the behavior of animals because landscape configuration affects how animals use land adjacent to roads (Singleton and Lehmhuhl 2000). For example, researchers claim that deer found between wooded areas in open landscapes, between fields in forested landscapes, and in conservation areas in the suburbs are more prone to being hit by a vehicle (Romin and Bissonette 1996; Forman and Alexander 1998; Forman and Deblinger 1998). A large number of studies on white-tailed deer populations in Pennsylvania (Bashore et al. 1985) suggested that foraging behaviors influenced movements and caused higher accidents rates in non-wooded areas (Romin and Bissonette 1996). From a study on mule deer in northeastern Utah, Romin & Bissonette (1996) reported that areas with higher percentages of vegetative cover had higher kills. In contrast, roads bordered by agricultural fields had less kills because fields provided foraging opportunities that drew deer away from roads. Finder et al. (1999) included 15 variables in an examination of characteristics associated with high collision areas. They found that the distance to forest cover was the most important predictor of high deer-vehicle collision sites; the greater this distance, the less probability that a road segment would be a high deer collision site. They also found that adjacent gullies, riparian corridors, public recreational areas and road bends may increase the probability of deer-vehicle collisions.

Topography may also affect deer movement patterns and foraging behavior because of the limits it places on species and their ability to access areas, as well as the impacts that it has on available food sources (Bellis and Graves 1971). Topography can create drainages or slopes that funnel animals closer to the road, putting them at more risk for vehicle collisions. A complete predictive model will consider a full complement of environmental and road variables, including landscape spatial pattern. By considering how these variables impact animal exposure (the proximity of animals to the road), it is clear that the causes of wildlife-vehicle collisions may be more fully understood. Wildlife population density and fluctuations impact collision patterns; a consideration of these factors may aid in describing and predicting areas of high wildlife-vehicle collisions (Rolley and Lehman 1992, Groot Bruinderink and Hazebroek 1996, Gunson and Clevenger 2003). Hughes et al. (1996) reported that the results of their animal crash rate analysis were constrained because relative locations and densities of animal populations were not included. Species presence is not constant across the landscape. A more complete picture of causal relationships in wildlife-vehicle collisions includes a consideration of how these factors affect animal and driver behavior.

Animal and Driver Behavior

Roads modify animal behavior as reflected in home range shifts, as well as altered movement patterns, reproductive success, escape responses, and physiological states (Trombulak and Frissell 2000). The data that we analyzed were not species specific but included all reported AVCs. Most collisions in our data set involved deer, elk, or moose. Species have different vulnerabilities to road mortality, depending on their life history characteristics and behavior. For example, those animals with high intrinsic mobility, as well as habitat generalists and those who must cross roads to migrate are most susceptible to road mortality (Forman et al. 2003). Behavior and habitat use patterns are different within and among wildlife species, implying the need for predictive models, and mitigation and management strategies that are specific to species, to the site, and take into account what is known about animal behavior. For example, Groot Bruinderink and Hazebroek (1996) pointed out the differences in behavior between ungulate species: red and roe deer tended to flee while fallow deer stood and waited in response to traffic. Because behavioral and habitat patterns differ, Romin and Bissonette (1996) suggested that the success of mitigation strategies may, in large part, be specific to the site and species. A model attempting to describe and predict factors contributing to areas of high road mortality would be most complete if it included a consideration of species-specific behavior in relation to various site-specific road and environmental variables (Clevenger 2006).

Driver behavior may also be used to describe wildlife-vehicle mortality. The way that drivers react to environmental and road variables and to animal behavior can affect the number of wildlife-vehicle collisions that occur; the interaction between drivers and these variables is needed to create a complete predictive model. Hartwig (1993) found that 60 % of collisions are caused by improper driver reaction. The presence of woods or gullies adjacent to the road was highly correlated with a high probability of deer-vehicle collisions, implying that this reduced visibility may have obstructed visibility for drivers and contributed to their inability to prevent a collision (Finder et al. 1999). Joyce and Mahoney (2001) stated that “human perception experience” may contribute to wildlife-vehicle collisions. Factors including fatigue, glare, and driver inability to distinguish similarly colored objects and estimate distance may all influence the frequency of collisions. Joyce and Mahoney (2001) stipulated that the type of driver may also have an impact. They attributed a summer peak in moose-vehicle collisions to a combination of moose reproductive and behavioral patterns and an increased number of naïve drivers who were traveling on unfamiliar roads. They suggested that these types of drivers may be more easily distracted. Mitigation measures can effectively address issues of motorist behavior. Forman et al. (2003) suggested improving the field-of-view so that drivers can see animals on the road side, managing traffic on roads during times when the risk for collisions may be highest (i.e., migration or dispersal), and implementing techniques to directly change motorist behavior (i.e., signs, education, remotely-sensed roadside lights).

Conclusions

Data on wildlife-vehicle collisions can be used for at least 2 different purposes: 1) hotspot analysis; and 2) predictive modeling. We illustrate the issues associated with creating models to explain wildlife-vehicle collisions using only road geometrics. We suggest that if the objective is to *define hotspots of road kill for mitigation action,* hotspot analyses that use existing data accurate to the mile marker produce excellent results and can be done for most state, province, or other municipalities who have such data immediately available. Use of hotspot analyses to prioritize mitigation measures will have quick beneficial effects on restoring landscape permeability. However, developing a reliable and accurate *predictive model* of animal-vehicle crashes using explanatory environmental and/or roadway variables requires that: 1) road kill data are spatially explicit, 2) data regarding explanatory variables and road kill are recorded at appropriate scale resolutions and extents, 3) data are recorded accurately and completely, 4) the model consider road geometrics and environmental variables, and 5) the model considers both driver behavior and animal behavior. We argue that consideration of these factors in correlation with spatially explicit wildlife-vehicle collision data will allow for the development of a model with predictive possibilities. If research is to inform decisions made by state wildlife and highway agencies, it will be most useful if data collection and analysis fulfills these requirements. Understanding the patterns and processes that lead to wildlife-vehicle collisions will allow us to develop practical preventative mitigation strategies.

Acknowledgements

We thank N. McCoy and D. Ramsey for helpful comments on the manuscript. The Utah Department of Transportation, the Utah Division of Wildlife Resources, the Bureau of Land Management , NCHRP Project 25-27 (Transportation Research Board, National Academies of Science and Engineering), and the Utah Cooperative Fish and Wildlife Research Unit provided funding for this project.

Table 1A. Correlations between wildlife-vehicle collisions and 3 explanatory road variables reported by authors based on data analysis.[a]

Author	Posted Speed Limit	Vehicle Speed	Traffic Volume
Allen & McCullough (1976)	N/A	SC	SC w/TOD.NSC seasonally.
Arnold (1978)	N/A	N/A	SC
Bashore et al. (1985)	NSC	N/A	N/A
Bellis and Graves (1971)	N/A	N/A	N/A
Brody and Pelton (1989)	N/A	N/A	SC
Carbaugh et al. (1975)	N/A	N/A	NSC
Case (1978)	N/A	SC	NSC
Clevenger et al. (2003)	N/A	N/A	NSC
Cristoffer (1991)	SC	N/A	NEGC (masked by speed)
Elzohairy et al. (2004)	N/A	N/A	N/A
Fahrig et al. (2001)	N/A	N/A	SC (w/ population trends)
Fahrig et al. (1995)	N/A	N/A	SC
Feldhammer (1986)	N/A	N/A	N/A
Finder et al. (1999)	N/A	N/A	N/A
Gunson and Clevenger (2003)	NSC	Y (cited)	NEGC (due to RT & PF)
Gunther et al. (1998)	SC	SC	N/A
Hughes et al. (1996)	N/A	N/A	N/A
Inbar and Mayer (1999)	N/A	N/A	SC (summer), NSC (winter)
Jahn (1959)	N/A	NSC	Source of bias in study
Joyce and Mahoney (2001)	SC (w/ injury)	SC(w/injury)	SC
Maine Interagency Work Group (2001)	SC (50-55mph)	Y	Y
Mansfield and Miller (1975)	N/A	NSC	NSC
Nielsen et al. (2003)	N/A	N/A	N/A
Pojar et al. (1975)	N/A	Y	N/A
Puglisi et al. (1974)	N/A	Y (cited)	Y (cited)
Rolley and Lehman (1992)	N/A	SC (PD)	NEGC (due to RT &PF)
Romin and Bissonette (1996)	N/A	SC	SC
Rost and Bailey (1979)	N/A	N/A	Y (affects deer & elk distribution)
Schwabe et al. (2002)	N/A	N/A	Y
Staines et al (2001)	N/A	Y	Y
Seiler et al. (2004)	N/A	N/A	Y
van Langevelde and Jaarsma (2004)	N/A	Y	SC

[a] Result abbreviations: N/A=not available/not considered, NC=negative correlation, NSC=no significant correlation, NEGC=negative correlation, SC=significant correlation, Y=Authors state factor has impact (no statistics cited). These are other factors considered to explain wildlife-vehicle collisions by authors who did not conclude that traffic volume, speed or speed limit were the only explanatory variables. Abbreviations: PD=population density, PF=population fluctuations, RT=road type, SD=Shannon's diversity index, TOD=time of day.

Table 1B. Correlations between wildlife-vehicle collisions and 3 explanatory road variables reported by authors based on literature.[a]

Author	Posted Speed Limit	Vehicle Speed	Traffic Volume
Cook and Daggett (1995)	N/A	Y	Y
Danielson and Hubbard (1998)	N/A	Y	Y
Forman and Alexander (1998)	Y	Y	Y
Forman et al. (2003)	N/A	Y	Y
Groot Bruinderink and Hazebroek (1996)	N/A	Y	Ambiguous (due to PF)
Knapp and Yi (2003)	N/A	Y	Y
Putnam (1997)	N/A	N/A	Y (affects movement patterns)
Trombulak and Frissell (2000)	N/A	Varies (w/species)	Y

[a] Result abbreviations: N/A=not available/not considered, Y=Authors state factor has impact (no statistics cited). These are other factors considered to explain wildlife-vehicle collisions by authors who did not conclude that traffic volume, speed or speed limit were the only explanatory variables. Abbreviations: PF=population fluctuations.

Table 2. Road statistics for 4 routes in Utah

route #	road length[a]	# deer crashes	accidents/mile	event density[a]
40	175.2	1858	10.61	0.63 - 4698
89	417.8	3360	8.04	0.20 - 94.87
91	45.6	584	12.81	0.70 - 33.33
189	29.2	396	13.55	1.27 - 37.78

[a] miles

[b] standardized number of animal-vehicle crashes per mile for each volume defined segment. See methods for further description

5

Figure Captions

Figure 1. Flow chart showing the process of creating the traffic volume data set for a portion of Route 40.

Figure 2. A) Traffic volume mean, median posted speed limit, and event density vs. section number for Route 91, Box Elder and Cache counties, Utah, 1992-2002. Event density is a rate and equals collisions per mile for each volume-defined section. B) Event density vs. median posted speed for Route 91. C) Event density vs. volume mean for Route 91. Expected relationship given as 45^0 line.

Figure 3. Scale issues involved with posted speed limit, mile post markers, and traffic volume variables. Because animal-vehicle crash databases are usually reported by mile marker or km marker, it is difficult or impossible to associate the relevant explanatory variables of speed limit and traffic volume with incident a standardized density (road kill) because they are measured at different extents and resolutions. See text for additional explanation.

Fig. 1

STEP 1: Extracted volume data for route 40 (1992-2002

Mileposts	2002	2001	2000	1999	1998	1997	1996	1995	1994	1993	1992
0 - 1.24	21145	20725	18953	18295	17260	16220	16865	16225	15490	14340	13500
1.24- 3.96	20262	19865	18165	17525	16530	15535	16870	16225	15490	14340	13500

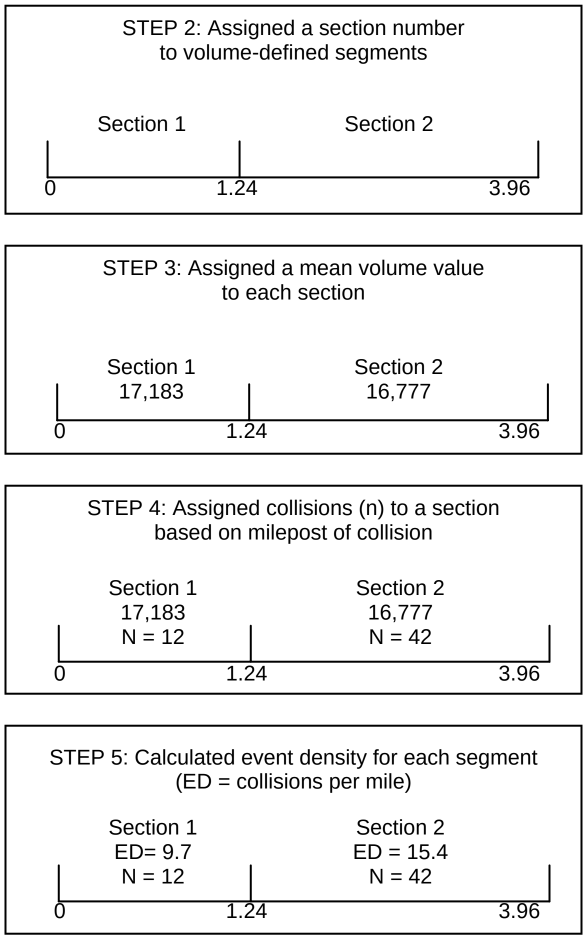


Fig 2A

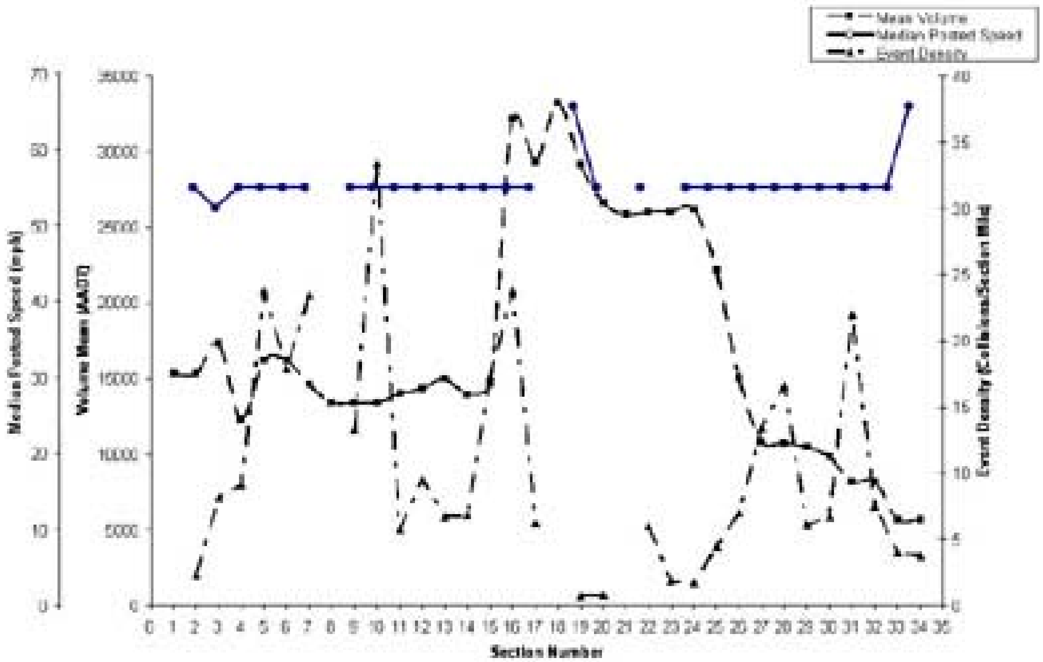


Fig 2B

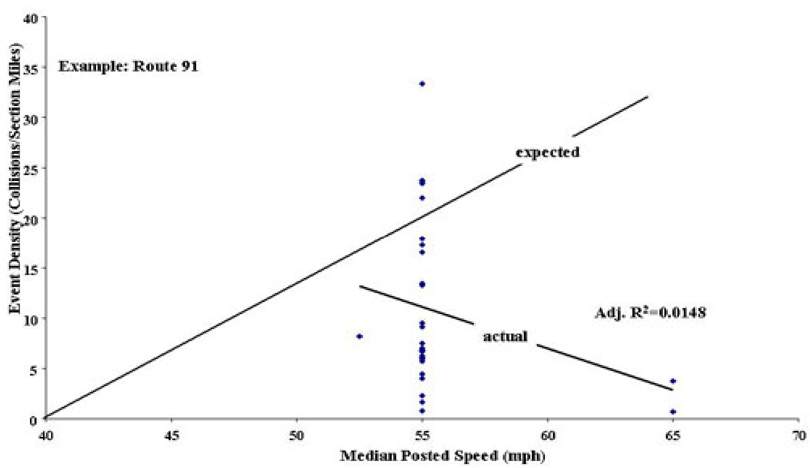


Fig 2C

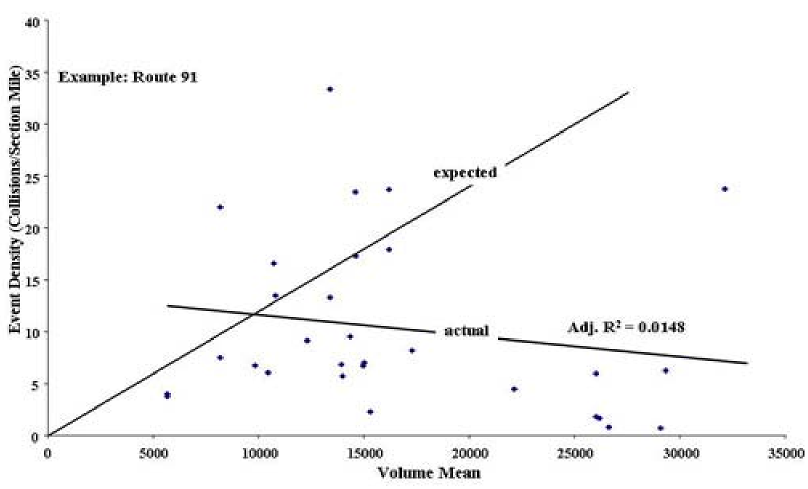
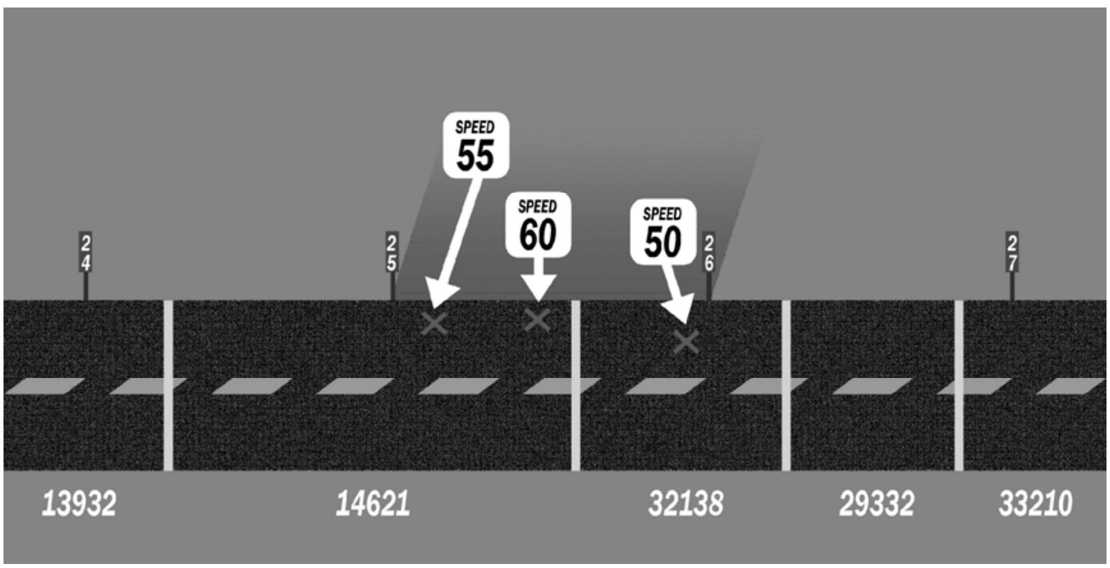


Fig. 3


SPEED
55
SPEED
60
SPEED
50
24
25
26
27
13932
14621
32138
29332
33210

References

Allen R. E. and McCullough D. R. 1976. Deer-car accidents in southern Michigan. Journal of Wildlife Management 40: 317-25.

Arnold D. 1978. Characteristics and cost of highway deer kills. *In* Kirkpatrick, C.M. (ed.), Proceedings of the 1978 John S. Wright Forestry Conference, pp 92-101. Department of Forestry and Natural Resources and Indiana Cooperative Extension Services, Purdue University, Lafayette, Indiana, USA.

Bashore T. L., Tzilkowski W. M., and Bellis E. D. 1985. Analysis of deer-vehicle collision sites in Pennsylvania. Journal of Wildlife Management 49: 769-74.

Bellis E. D. and Graves H. B. 1971. Deer mortality on a Pennsylvania interstate highway. Journal of Wildlife Management 35: 232-7.

Bissonette J. A. 2002. Scaling roads and wildlife: the Cinderella Principle. Zeitschrift Fur Jagdwissenschaft Supplement 48: 208-14.

Brody A. J. and Pelton M. R. 1989. Effects of roads on black bear movements in western North Carolina. Wildlife Society Bulletin 17: 5-10.

Carbaugh B., Vaughan J. P., Bellis E. D., and Graves H. B. 1975. Distributions and activity of whitetail deer along an interstate highway. Journal of Wildlife

Management 39: 570-81.

Case R. M. 1978. Interstate highway road-killed animals: a data source for biologists. Wildlife Society Bulletin 6: 9-13.

Clevenger A. P., Chruszcz B., and Gunson K. E. 2001. Highway Mitigation Fencing Reduces Wildlife-Vehicle Collisions. Wildlife Society Bulletin 29:646-653.

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

Clevenger A. P., Chruszcz B., and Gunson K. E. 2003. Spatial patterns and factors influencing small vertebrate fauna road-kill aggregations. Biological Conservation 109: 15-26.

Clevenger A. P. and Waltho N. 2005. Performance Indices to Identify Attributes of Highway Crossing Structures Facilitating Movements of Large Mammals. Biological Conservation 121:453-464.

Clevenger A. P., Hardy A., Gunson K. E. 2006. Limiting effects of road-kill reporting data due to spatial inaccuracy. *In* Bissonette, J. A. (ed.), Evaluation of the Use and Effectiveness of Wildlife Crossings, pp. 76-93. Second Interim Report, National Academies of Science and Engineering, Transportation Research Board NCHRP 25-27 FY04, Washington D. C., USA.

Cook K. E. and Daggett P.-M. 1995. Highway road kill, safety, and associated issues of safety and impact on highway ecotones. Task Force on Natural Resources, Transportation Research Board National Research Council, Washington, D.C., USA.

Cristoffer C. 1991. Road mortalities of northern Florida vertebrates. Quarterly Journal of the Florida Academy of Sciences 54: 65-8.

Danielson B. J., and Hubbard M. W. 1998. A literature review for assessing the status of current methods of reducing deer-vehicle collisions. The Task Force on Animal Vehicle Collisions, The Iowa Department of Transportation, and The Iowa Department of Natural Resources, Ames, Iowa, USA.

Elzohairy Y. M., Janusz C., and Tasca L. 2004. Characteristics of motor vehicle-wild animal collisions: An Ontario case study. *In* Proceedings of the Transportation Research Board 83rd Annual Meeting, pp. 1-15. Washington, D.C., USA.

Fahrig L., Neill K. E., and Duquesnel J. G. 2001. Interpretation of joint trends in traffic volume and traffic-related wildlife mortality: a case study from Key Largo, Florida. Proceedings of the International Conference on Environment and

Transportation 2001: 518-21.

Fahrig L., Pedlar J. H., Pope S. E., Taylor P. D., and Wegner J. F. 1995. Effect of road traffic on amphibian density. Biological Conservation 74: 177-82.

Feldhamer G. A., Gates J. E., Harman D. M., Loranger A., and Dixon K. J. 1986. Effects of interstate highway fencing on white-tailed deer activity. Journal of Wildlife Management 50: 496-503.

Finder R. A., Roseberry J. L., and Woolf A. 1999. Site and landscape conditions at white-tailed deer/vehicle collision locations in Illinois. Landscape and Urban Planning 44: 77-85.

Forman, R. T. T. 1998. Road ecology: a solution for the giant embracing us. Landscape Ecology 13: iii-v.

Forman R. T. T., and Alexander L. E. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29: 207-31.

Forman, R.T.T. and R.D. Deblinger. 1998. The ecological road-effect zone for transportation planning and Massachusetts highway example. International Conference on Wildlife, Environment, and Transportation 1998: 78-83.

Forman R. T., Sperling D., Clevenger A. P., Bissonette J. A., 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. 2003. Road ecology: Science and Solutions. Island Press, Washington, D.C.

Groot Bruinderink G. W. T. A. and Hazebroek E. 1996. Ungulate traffic collisions in Europe. Conservation Biology 10: 1059-67.

Gunson K. E. and Clevenger A. P. 2003. Large animal-vehicle collisions in the central Canadian Rocky mountains: patterns and characteristics. Proceedings of the International Conference on the Environment and Transportation 2003: 355-365.

Gunther K. A., Biel M. J., and Robison H. L. 1998. Factors influencing the frequency of road-killed wildlife in Yellowstone National Park. Proceedings of the International Conference on Wildlife, the Environment and Transportation 1998: 32-40.

Hartwig D. 1993. Auswertung der durch Wild verursachten Verkehrsunfalle nach der Statistik fur Nordhein-Wetsfalen. Zeitschrift fur Jagdwissenschaft 39: 22-33.

Hughes W. E., Saremi A. R., and Paniati J. F. 1996. Vehicle-animal crashes: an increasing safety problem. Institute of Transportation Engineers Journal 66: 24-8.

Inbar M., and Mayer R. T. 1999. Spatio-temoral trends in armadillo diurnal activity and road-kills in central Florida. Wildlife Society Bulletin 27: 865-72.

Jahn L. R. 1959. Highway mortality as an index of deer population change. Journal of Wildlife Management 23: 187-96.

Joyce T. L. and Mahoney S. P. 2001. Spatial and temporal distributions of moose-vehicle collisions in Newfoundland. Wildlife Society Bulletin 29: 281-91.

Knapp K. K. and Yi X. 2003. Deer-vehicle crash patterns and proposed warning sign installation guidelines. Report to the Wisconsin Department of Transportation, Madison, Wisconsin, USA. 22 pp.

Maine Interagency Work Group on Wildlife/Motor Vehicle Collisions. 2001. Collisions between large wildlife species and motor vehicles in Maine. Interim Report. Maine Interagency Work Group of Wildlife/Motor Vehicle Collisions, Augusta, Maine, USA. 24 pp.

Malo J. E., Suarez F., and Diez A. 2004. Can we mitigate animal-vehicle accidents using predictive models? Journal of Applied Ecology 41: 701-10.

Mansfield T. M. and Miller B. D. 1975. Highway deer-kill district 02 regional study. Caltrans Internal Report. Sacramento, California, USA. 49 pp.

McCaffrey K. R., 1973. Road-kills show trends in Wisconsin deer populations. Journal of Wildlife Management 37:212-216.

Morrison M. L., Marcot, B. G., and Mannan R. W. 1992. Wildlife-Habitat Relationships. University of Wisconsin Press, Madison, Wisconsin, USA.

Nielsen C. K., Anderson R. G., and Grund A. D. 2003. Landscape influences on deer-vehicle accident areas in an urban environment. Journal of Wildlife Management 67: 46-51.

Pojar T. M., Prosence R. A., Reed D. F., and Woodard T. N. 1975. Effectiveness of a lighted, animated deer crossing sign. Journal of Wildlife Management 39: 87-91.

Puglisi M. J., Lindzey J. S., and Bellis E. D. 1974. Factors associated with highway mortality of white-tailed deer. Journal of Wildlife Management 38: 799-807.

Putnam R. J. 1997. Deer and road traffic accidents: options for management. Journal of Environmental Management 51: 43-57.

Rolley R. E. and Lehman L. E. 1992. Relationships among raccoon road-kill surveys, harvests, and traffic. Wildlife Society Bulletin 20: 313-8.

Romin L. A. (1994). Factors associated with the highway mortality of mule deer at Jordanelle Reservoir, Utah. Master's Thesis. Utah State University, Logan, Utah, USA. 75pp.

Romin L. A., and Bissonette J. A. 1996. Temporal and spatial distribution of highway mortality of mule deer on newly constructed roads at Jordanelle Reservoir, Utah. The Great Basin Naturalist 56: 1-11.

Rost G. R., and Bailey J. A. 1979. Distribution of mule deer and elk in relation to roads. Journal of Wildlife Management 43: 634-41.

Schwabe K. A., Schuhmann P. W., Tonkovich M. J., and Wu E. 2002. An analysis of deer-vehicle collisions: the case of Ohio. Human conflicts with wildlife: economic considerations. *In* Clark, L (ed.), Proceedings of the Third National Wildlife Research Center Special Symposium on Human Conflicts with Wildlife: Economic Considerations, pp 91-103. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center, Fort Collins, CO, USA.

Seiler A. 2004. Road mortality in Swedish mammals: results of drivers' questionnaire. Wildlife Biology 10: 225-33.

Singleton P.H. and J. F. Lehmkuhl. 2000. I-90 Snoqualmie Pass Wildlife Habitat Linkage Assessment. USDA Forest Service Report WA-RD 489.1., Washington State Department of Transportation.

Staines B., Langbein J., and Putnam. R. 2001. Road traffic accidents and deer in Scotland: Executive summary to the Ministry of Agriculture Fisheries and Foods, pp. 1-102. Scotland.

Trombulak S. C. and Frissell C. A. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14: 18-30.

van Langevelde F. and Jaarsma C. F. 2004. Using traffic flow theory to model traffic mortality in mammals. Landscape Ecology 19: 895-907.

Zar J. H. 1999. Biostatistical analysis. Prentice Hall, Upper Saddle River, New Jersey, USA.