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Landscape and traffic factors influencing deer–vehicle collisions in an urban enviroment

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Abstract: Deer–vehicle collisions (DVCs) are steadily increasing across North America. The increase is particularly pronounced in urban green spaces where deer (*Odocoileus* spp.) populations and road densities are high. In the greater city of Edmonton, Alberta, Canada, 333 DVCs occurred from 2002 to 2004. To identify landscape and traffic correlates of these collisions, we built 3 statistical models. The first model assessed the importance of local variables and was based on a spatial precision of the nearest intersection to which collisions were referenced. The second model was based on landscape characteristics and used the nearest township intersection to aggregate collisions. For each of the models, we generated an equivalent number of random locations in a geographic information system (GIS) and examined several independent variables at 4 spatial scales (using 100-m, 200-m, 400-m, and 800-m radius buffers). We used multivariate logistic regression to determine which landscape and traffic factors increased the probability of a DVC. The third model used ordinal regression to assess correlates with collision frequency. Our first (High Precision) model showed that DVCs occurred in areas with high speed limits and low densities of roads within an 800-m buffer. The second (Aggregate) model found DVCs more likely to occur in areas close to water and the combination of high road densities and non-forested vegetation of high productivity within 800 m. The third (Hotspot) model identified only high traffic speed as a correlate of collision frequency. A temporal analysis of the collision data found that DVCs peaked in mid-November. We conclude that rates of DVCs could be reduced and road safety improved by lowering speed limits during peak seasons, particularly in areas where road density is high (i.e., interchanges) and where non-forested vegetation occurs in close proximity to roads. Several aspects of our analyses and results may have applications in other jurisdictions where DVCs occur.

Key words: deer–vehicle collision, human–wildlife conflict, *Odocoileus* spp., road-kill, road safety, urban deer, urban ecology

Deer–vehicle collisions (DVCs) are steadily increasing across North America (Jensen 1995, Romin and Bissonette 1996) and other developed countries (Groot Bruinderink and Hazebroek 1996). Every year in the United States, >1 million vehicle collisions involve deer (*Odocoileus* spp.), resulting in >$1 billion worth of property damage and >200 lost human lives (Conover et al. 1995). The problem of DVCs is particularly pronounced in urban areas where high densities of white-tailed deer (*Odocoileus virginanus*) occur (Alverson et al. 1988). In these same areas, urbanization is also associated with rapid increases in both human population and road density (Squires 2002), thus increasing the potential for DVCs.

The rising number of DVCs has spurred several studies to examine the correlates of collision locations (reviewed by Malo et al. 2004). Previous studies have shown that DVCs are not spatially or temporally random and that both local habitat (small-scale) and landscape (large-scale) factors can be correlated with collisions (Hussain et al. 2007, Grovenburg et al. 2008). As examples, Finder et al. (1999) found that landscape heterogeneity and distance of forest cover from the road were important predictors of DVCs, while Hubbard et al. (2000) found that collisions were frequently near elevated roadways. In an urban environment, DVCs were more common as the number of buildings and number of adjacent public land patches increased (Nielsen et al. 2003). These diverse findings make it difficult to generalize about the correlates of DVCs.

There are several reasons why it is difficult to identify generalized characteristics of DVCs. (1) Studies have been conducted at many spatial scales. Most studies have emphasized local habitat characteristics (e.g., Puglisi et al. 1974, Nielsen et al. 2003), whereas few have examined characteristics of surrounding landscapes (e.g., Hubbard et al. 2000, Malo et al. 2004, McShea et al. 2008). Both local and landscape scales are likely to be important because herbivores respond to many spatial scales when selecting habitat (Johnson et al. 2002, Apps et al. 2001, Kie et al. 2002, Hobbs 2003). Focusing on 1 scale would likely overlook significant relationships at other spatial scales. Therefore, analyses of a dataset at multiple scales are ideal. (2) Deer–vehicle collisions are difficult to generalize because collisions occur in many regions and ecotypes. Consequently, important predictors of collisions likely differ among areas, making it important to conduct studies across an equivalent range of conditions. (3) Jurisdictions may record DVCs with varying precision. (4) Temporal variation in collision frequency results from seasonal changes in the behavior and movement rates of deer (e.g., Jensen 1996, Grund et al. 2002).

The ability to predict the locations of DVC sites is particularly important because of the increasing prevalence of both deer and vehicle traffic (Grund et al. 2002, Storm et al. 2007, Bissonette and Kasser 2008). Only 1 previous study specifically examined DVCs in an urban environment (Nielsen et al. 2003), and only 1 other included traffic characteristics (Finder et al. 1999). In our study, we used Geographic Information Systems (GIS) to examine correlates of year-round DVCs, traffic characteristics, and environmental factors at several spatial scales and with 2 levels of precision in the urban environment of Edmonton, Alberta, Canada.

Methods

Study area

We studied DVCs in the metropolitan area of Edmonton, which is located in the aspen (*Populus tremuloides*) parkland ecoregion of Canada. Edmonton is Canada's sixth largest city, with >1 million residents, and is bisected diagonally by the North Saskatchewan River valley. Totaling 7,400 ha, the river valley and associated ravines create one of the largest expanses of urban parkland in North America (City of Edmonton 2007*a*). In addition to the river valley, Edmonton has >460 parks (City of Edmonton 2007*b*), composed of open vegetated spaces and forest predominantly composed of aspen (*Populus* spp.), spruce (*Picea* spp.), and shrubby riparian areas. Outlying areas of the city are dominated by agricultural fields, which include, in order of abundance, canola (*Brassica napus napus*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*Avena sativa*), and peas (*Pisum sativum arvense*; E. Bork, personal communication) interspersed with patches of aspen. This combination of open areas with high-quality forage and dense forest patches for cover provide ideal habitat for deer (Banfield 1974). Owing to its continental climate with an annual average temperature of 1.8°C, the area is typified by harsh winters and warm summers.

Aerial view of downtown Edmonton, Alberta, Canada, showing part of an extensive river valley park.

Edmonton has recently experienced rapid growth of major roadways and traffic volume along suburban arterial roadways in both residential and industrial areas (City of Edmonton 2007*c*). Traffic volumes are increasing in the river valley where the busiest river crossing, Quesnell Bridge, averages 113,100 vehicles per day and is increasing by ~1.2% annually (City of Edmonton 2005). Furthermore, significant increases in traffic volume also occur along commuter traffic routes and arterial roads (e.g., Whitemud Freeway >100,000 vehicles/day, Anthony Henday, St. Albert Trail, and Calgary Trail >35,000 vehicles/day each; City of Edmonton 2007*c*). The road network around the outskirts of Edmonton is also undergoing expansion as a result of new residential and industrial developments amid a matrix of primarily agricultural lands.

Characterizing deer–vehicle collision locations

To characterize the locations of DVCs, we used a database provided by Edmonton Bylaw Services, which identified the location of all reported collisions involving deer. There were 115, 101, and 117 DVCs in 2002, 2003, and 2004, respectively, but not all collisions represented unique locations, because some intersections experienced >1 collision. The database recorded the date of collision and referenced DVCs to the street or avenue names of the nearest intersection. We used ArcGIS 8.3 (Environmental Systems Research Institute, Redlands, Calif.) to digitize these known collision locations onto a digital street map of Edmonton (City of Edmonton 2003*c*) and subsequently used these collision locations as the unit of analysis. This meant that in the city center, the database generally had a precision of approximately 50 m, whereas locations on the perimeter of the city were based on the township grid where roads typically occur every 800 m, to yield a precision of 400 m.

Using logistic and ordinal regression, we developed 3 models to examine correlates of DVCs. We called the first model a High Precision model, and we digitized known collisions that occurred to closest intersections where they were referenced in the database. We called our second model an Aggregate model and used it to standardize the precision of accident locations. For this model, collisions were referenced to the nearest intersection on the grid system of township and range, where a right-of-way is designated every 1.6 km east–west and 3.2 km north–south. This grid system is used throughout Canada and many parts of the United States; therefore, this analysis is potentially appropriate to compare correlates across jurisdictions and landscapes. For these 2 models, we paired random intersections where deer accidents could occur (available sites) with collision sites. We characterized habitat and traffic attributes at each random location (n = 204 for High Precision model and n = 155 for Aggregate model). We constrained random locations to avoid overlapping and did not allow them to occur on known DVC sites. We called the third analysis a Hotspot model and used ordinal regression to examine correlates of collision frequency at all the intersections (n = 170) that exhibited ≥1 DVC. We grouped collisions that occurred within 300 m of each other as in a Hotspot, using the central location as the point of reference.

We examined habitat attributes at several spatial scales, primarily because deer may respond differently to potential factors at different scales, but also to explore the low locational accuracies at the city margins. To achieve this multi-scale approach, we measured habitat variables for each collision and control location within 4 different radii: 100 m, 200 m, 400 m, and 800 m that corresponded to areas of 0.03, 0.13, 0.50, and 2.01 km^2.

Landscape and traffic factors

Landscape and traffic attributes of DVCs were analyzed using ArcGIS 8.3. We derived land-cover information from a combination of existing land-use data. Street network, land use, and traffic bylaw were provided by GeoEdmonton at the 1:20,000 scale, (City of Edmonton 2003). GeoGratis, a free web-based program of the Canadian federal government, provided Landsat 7 satellite imagery at 30-m resolution (Natural Resources Canada 2004), and Natural Resources Canada's National Topographic Database supplied forest

Highway interchange showing the combination of proximity to water, high-speed traffic, complex road configurations, and non-forested vegetation where DVCs are more likely to occur.

vegetation, and water data at the 1:50,000 scale (Natural Resources Canada 1996).

We generated 5 land-cover classes from land-use data and landscape features: (1) urban-residential, comprising residential neighborhoods; (2) urban-nonresidential, comprising industrial, business, and commercial areas; (3) vegetation–non-forest, comprising open green space, such as agriculture, clearings, meadows, and recreational open space; (4) vegetation–forest, comprising wooded spaces; and (5) water feature, comprising rivers, wetlands, and lakes.

Urban areas were separated into residential and nonresidential because residential areas tend to have more planted vegetation that is attractive as forage to deer, while nonresidential areas included industrial zoning and commercial areas that were mostly devoid of vegetation. Agriculture, clearings, meadows, and recreational open space were collapsed into a category described as non-forested vegetation because these land-use types essentially provide forage for deer (Kie et al. 2002).

For the 3 categories of biological relevance to deer (forested vegetation, non-forested vegetation, and water), we generated 3 groups of variables from the landcover classes: (1) distance from intersection to nearest feature type (i.e., nearest forest and water); (2) proportion of landcover type within buffers; and (3) edge densities of features (i.e., the sum of water edge and forest edge) within buffers. Landscape variables, such as proportion and edge densities, were calculated using neighborhood statistics within a circular moving window at each spatial scale.

As a surrogate for primary productivity, we used normalized difference vegetation index (NDVI) to assess the concentrations of green vegetation (Jensen 1996). At each spatial scale, mean NDVI around each collision and control site were extracted from a derived digital layer, computed from the difference of near-infrared minus red reflectances divided by the sum of reflectance in near-infrared and red ranges, as recorded by a Landsat 7 Thematic Mapper satellite scene taken on August 15, 2001 (Natural Resources Canada 2001).

Deer–vehicle collisions were intersected with landscape variables using Hawths Tools extensions to extract the landscape variable within each scale (Beyer 2004). Each model's final landscape variables that were hypothesized to be most biologically meaningful included distance to nearest water, distance to nearest forest patch (minimum 30 m^2), proportion of nonforested vegetation and forest, edge density of roads, water, forest, and mean NDVI within each scale.

As measures of traffic characteristics, we categorized mean daily traffic volume and speed limit. Speed limits from a digital speed bylaw layer provided by GeoEdmonton (City of Edmonton 2003) were classified from municipality designations into 3 categories: low (≤50 km/hr), medium (60–70 km/hr), and high (≥80 km/hr). Average annual weekday traffic volume at each of our locations was derived from a traffic volume database for 2002 (City of Edmonton 2007*c*). Traffic volumes were also broken into 3 categories corresponding to the city's road classification as local (<1,200 vehicles/day), collector (1,200–15,100 vehicles/day), and arterial (>15,100 vehicles/day). Traffic volume and speed limit were highly positively correlated; therefore, only speed was included in the final analysis, because adjusting speed is a more realistic management tool than adjusting traffic volume.

Statistical analyses

All statistical tests were performed using SPSS v11.5 (Chicago, Ill.) or SAS v9.1 (Cary, N.C.). Proportional data were arcsine-transformed to normalize their distributions (Zar 1998), and autocorrelated ($r \geq 0.7$) variables were eliminated by choosing the more significant and biologically meaningful variable from univariate tests. Remaining variables were assessed for their linearity by comparing the performance of each linear term with its quadratic counterpart with a likelihood ratio test. To avoid the pseudoreplication that would result from analyzing the several concentric buffers generated for habitat variables at each location, we identified and retained only the most significant scale of each variable.

We built a logistic regression model using collision and control points and Hosmer and Lemeshow's (1989) strategy. We began by identifying liberally significant ($P \leq 0.25$) main effects with univariate tests. We input all these effects into a single model and retained those that remained significant at $P \leq 0.05$. Eliminated variables were checked for confounding effects by assessing the change in beta coefficients of the remaining variables. We then fit a forced-entry reduced model with only those significant variables. We listed biologically plausible 2-way interactions among all variables and then entered each separately into the reduced main-effects model, retaining variables that were significant with a likelihood ratio test ($P \leq 0.05$). For habitat proportion data, only interactions of the same spatial scale were considered. Unscaled variables (e.g., the distance variables) were tested with every scale for variables describing habitat proportions. For example, we tested distance from the intersection to nearest water with proportion of forest at the 100-m, 200-m, 400-m, and 800-m scales. We assessed the fit of our models to the data using 2 measures: Nagelkerke's r^2 to assess the strength of association between the dependent and independent variables and the Hosmer and Lemeshow (1989) test to measure the goodness of fit (χ^2 GOF). For this test, high P values indicate a good fit to the data. All statistical tests were 2-tailed. We used a similar model-building strategy for the Hotspot analysis using SAS v9.1. Proc Glimmix was used to conduct a generalized linear mixed model, with a Poisson (rather than normal) error distribution in the response variable. Statistical models were constructed, allowing us to test the relationships between the independent variables and the number of accidents at individual intersections.

Model validation

For the 2 logistic regression models, we evaluated the predictive performance of our main effect models by running a k-fold cross-validation on our data sets. Using Huberty's rule of thumb (1994), data were randomly divided into 5 folds (80%) for model training, and 20% of the data were withheld for testing. Using logistic regression, data from the training model were used to predict habitat and traffic factors generated by the test data, after Boyce et al. (2002). These cross-validations were repeated 5 times, each time with a different fold of the data withheld as validation data. To investigate the performance of each validation model, the model values were divided into 10 equal-size bins (fixed intervals), and the validation points in each bin were counted. Validation for model performance was done using Spearman's rank correlation coefficients from model values and validation points; a positive correlation indicates a good predictive model. The Spearman's rank correlation coefficients were averaged to produce an overall indicator of model performance (Boyce et al. 2002).

Temporal analysis

To determine the temporal component of DVCs, we examined the date of collisions in each of the 3 study years using circular statistics.

Table 1. Habitat and traffic variables measured at DVCs and random intersections. We hypothesized that DVCs were negatively correlated with road density and distance to nearest forest patch and nearest water source, and that the remaining variables were positively correlated to DVCs.

Variable	Definition	Hypothesized effect
Forested	Proportion of forest spaces (%)	+
Non-forested	Proportion of non-forested vegetation, including meadows and farmland (%)	+
Road density	Sum of road lengths (km)	–
Forest edge density	Sum of edges where forest meets non-forested vegetation (m)	+
D_Forest	Distance to nearest forested patch (km)	–
D_Water	Distance to nearest water body (km)	–
Vegetation productivity	Average primary productivity as measured by NDVI	+
Speed	Speed limit as low (<50 km/hr), medium (60–70 km/hr), or high (>80 km/hr)	+
Traffic volume	Number of vehicles/day	+

Table 2. Coefficients for habitat and traffic factors influencing DVCs from our reduced High Precision and Aggregate models.

Variable	ß	SE	Wald	*DF*	*P*	Odds ratio
High Precision model						
Speed						
Low			63.9	2	0.0001	
Medium	1.91	0.032	36.9	1	0.0001	6.78
High	2.82	0.43	42.63	1	0.0001	16.83
Road density	0.0001	0.0001	55.66	1	0.0001	~1.00*
Constant	-0.123	0.486	0.064	1	0.800	
Aggregate model						
Distance to nearest water	0.0001	0.0001	3.96	1	0.047	~1.00*
Road density *x*% vegetation productivity	0.0001	0.0001	5.04	1	0.025	~1.00*
Road density *x*% of nonforested vegetation	0.0001	0.0001	25.33	1	0.0001	~1.00*
Constant	-0.714	0.265	7.27	1	0.007	

* The large range of these variables meant that an increase of a single unit produced >1% change in the odds of a DVC occurring.

This procedure required that we convert each date measurement to an angular equivalent (Zar 1999) such that January 1 is represented by 0 on a compass and December 31 is represented by 360. We then plotted the distribution of dates for each year in a circular frequency histogram with bins of 20° and compared these observations with the assumptions of a unimodal distribution (i.e., a Rayleigh test).

Results

In the preliminary univariate tests comparing DVCs and random locations, all variables (Table 1) were liberally significant at all the scales tested ($P \leq 0.25$). We included the most significant scale of each multiscale variable in our main effects model (Table 2). To the reduced main effects model, we then sequentially added biologically plausible 2-way interactions involving the variables forest edge density, road density, water edge density, distance to forest and water, and proportion of forest and nonforested vegetation.

High Precision model

Deer–vehicle collisions were twice as likely to occur in areas with high speed limits and areas with low densities of roads within 800 m (Table 2; -2LL = 324.4, $df = 2$, $P > 0.05$). For the 204 unique DVC locations, we compared habitat and traffic characteristics to 204 randomly chosen locations. Average posted speed limits were 41% higher at sites with DVCs than at random sites (posted speed limits mean ±SD = 72.8 ± 16.3 km/hr and 51.8 ± 4.9 km/hr, respectively. The number of DVCs increased dramatically as posted speed limits increased (Figure 1), whereas the vast majority of random sites (aligning with the majority of city area) occurred in the lowest speed category. This disparity was strongly apparent in the odds ratios produced by the model (Table 2). Relative to low speed sites, DVCs were 7 times more likely, in the medium speed category and 17 times more likely, at high speeds.

Deer–vehicle collisions were also more likely to occur in areas with lower road density (11.0 ± 7.4 km = $\bar{x}$ ± SD within 800 m buffer) than the random locations (21.1 ± 61.4 km; ß < 0.001; Wald = 55.8; $P < 0.001$). Likelihood-ratio tests did not reveal any significant interactions among the 24 combinations tested. The final reduced model showed strong association between independent and dependent variables (model $\chi^2 = 241.18$, $df = 3$, model $P \leq 0.001$, Nagelkerke's $r^2 = 0.60$), but it did not provide a good fit to the data Hosmer Lemeshow test (χ^2 GOF = 12.5, $df = 8$, $P = 0.13$). Deer–vehicle collisions and random sites were predicted with 80% and 88% accuracy, respectively.

Aggregate model

For the collisions aggregated to the nearest township intersection, the final reduced model showed that DVCs were more likely to occur near water (-2LL = 390.8, $df = 3$, $P < 0.05$; Table 2). Sites with DVCs (155 sites) were 29% closer to water than were random locations (155 sites; $\bar{x} \pm SD =$

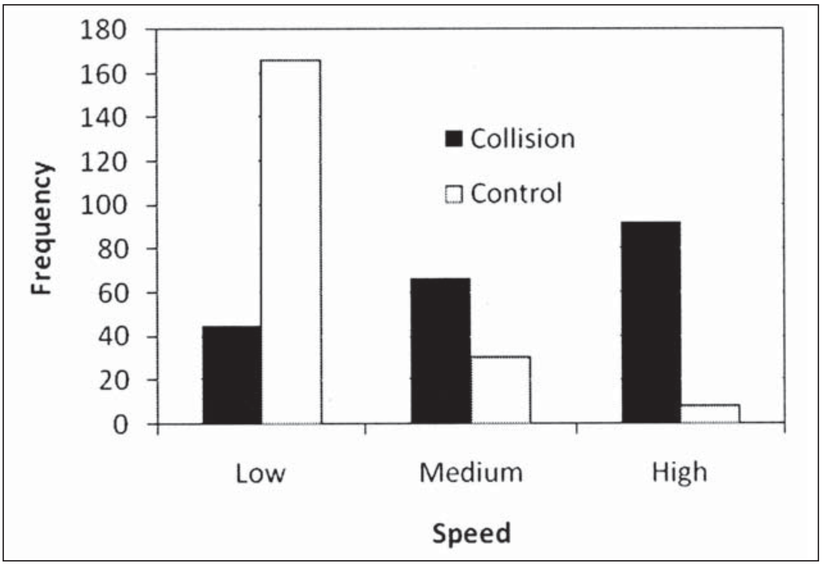

Figure 1. Frequency histogram of DVCs (black bars) and control locations (white bars) across 3 categories of speed: low (≤50 km/hr), medium (60–70 km/hr), and high (≥80 km/hr). Data based on DVCs in Edmonton, Alberta, Canada, in 2002, 2003, and 2004.

Table 3. Means and standard deviations of independent variables measured at DVCs and random intersections. Data were collected within 800-m buffers using both our High Precision and Aggregate models.

Variable	DVC	Random
High precision model		
Forest (%)	22.7 ± 22.7	12.7 ± 15.8
Non-forested (%)	76.5 ± 32.5	45.0 ± 23.4
Road density (km)*	11.0 ± 7.42	21.1 ± 6.14
Forest edge density (km)	2.20 ± 2.28	1.37 ± 1.96
D_Forest (km)	0.52 ± 0.55	1.00 ± 0.85
D_Water (km)	0.53 ± 0.47	1.07 ± 0.90
Vegetation productivity	0.10 ± 0.14	–0.04 ± 0.08
Speed (km/hr)*	72.8 ± 16.3	51.8 ± 4.90
Traffic volume	24,775 ± 24,577	n/a†
Aggregate model		
Forest (%)*	19.4 ± 19.9	19.0 ± 20.4
Non-forested (%)	78.1 ± 34.3	80.3 ± 42.7
Road density (km)*	10.9 ± 0.79	10.4 ± 10.3
Forest edge density (km)	1.94 ± 2.19	1.95 ± 2.32
D_Forest (km)	0.56 ± 0.57	0.68 ± 0.75
D_Water (km)*	0.56 ± 0.47	0.73 ± 0.65
Vegetation productivity*	0.09 ± 0.15	0.10 ± 0.16

* Significant variables (see Table 2).

† Information on traffic volume at random intersections is unavailable because traffic counters typically are not placed on low-traffic roads, but, rather, they are placed on high-traffic roads, such as arterials and freeways, where DVCs are more likely to occur.

0.56 ± 0.47 km and 0.73 ± 0.65 km, respectively; ß < 0.001, Wald = 3.96, $P = 0.05$; Table 3). Of the 10 2-way interactions tested, likelihood-ratio tests revealed that two were significant: road density by vegetation productivity and road density by proportion of non-forested vegetation. These meant that DVCs were more likely to occur in areas with high road density (measured within 800 m of a township intersection) that were also highly productive (as measured by NDVI; ß < 0.001, $P = 0.025$) or had abundant non-forested vegetation (ß < 0.001, $P \leq 0.001$). The final reduced model was not as strongly associated as our High Precision model ($\chi^2 = 39.0$, $df = 3$, $P \leq 0.001$, Nagelkerke's $r^2 = 0.16$), but it fit the data better (χ^2 GOF = 6.81, $df = 8$, $P = 0.56$). Deer–vehicle collisions and random sites were predicted by this model with 71% and 60% accuracy, respectively.

Model validation. Using k-fold cross-validation, both models displayed significant Spearman rank correlations, indicating good model performance. However, our Aggregate model performed better (mean $r_s = 0.98$, $P < 0.001$) than our High Precision model (mean $r_s = 0.67$, $P = 0.04$). Individual validations of the Aggregate model were more consistently significant (all 5-model sets were significant) than the High Precision sets (2 of 5 sets were significant, $P \leq 0.05$). Although the Aggregate model performed better than our High Precision model, we consider both models to be predictive overall.

Hotspot model

We grouped collisions that were within 300 m of one another to identify hotspots of collision frequency. Collisions at these 170 sites ranged from 1 to 13 ($\bar{x} = 1.86$, SD = 1.76), and 27 sites exhibited more than 2 collisions. Only speed was important in predicting collision frequency ($F_{2,167} = 12.02$, $P < 0.001$). Of the 27 sites that exhibited >2 collisions, nineteen occurred on roads with the highest speed limit category (≥ 80 km/hr).

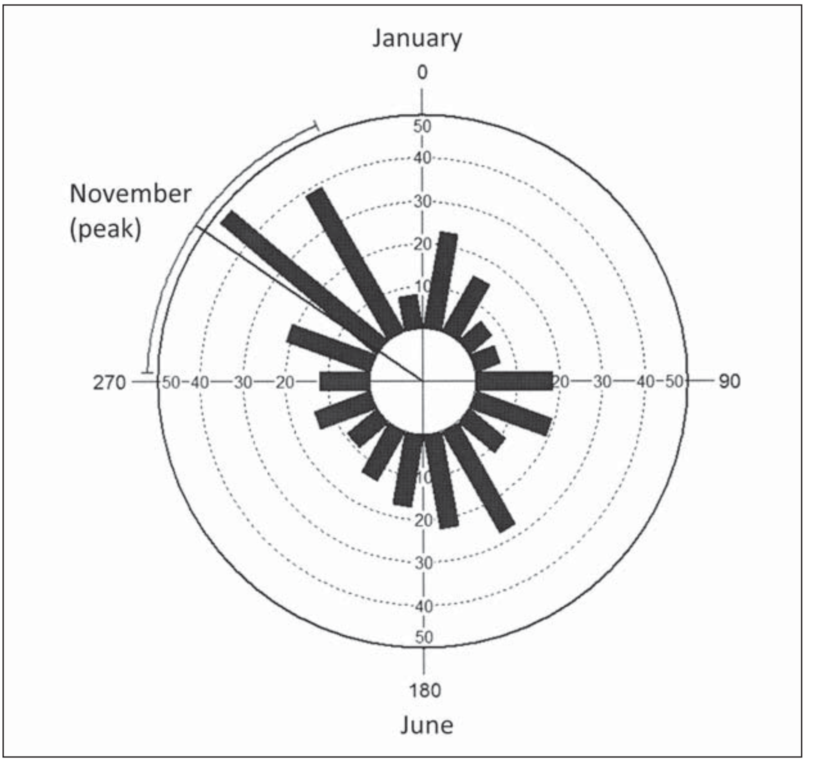

Figure 2. Circular histogram of DVCs in area of Greater Edmonton, Alberta, Canada, 2002–2004, inclusive. Dates are binned into 20-day increments; 0 represents January 1, and the subsequent quartiles represent approximately April 1, July 1, and October 1, respectively. Concentric circles describe the number of observations in each bin; the mean vector (~ November 10) is connected to the 95% confidence interval on the plot circumference.

Temporal analysis

The temporal distribution of collisions exhibited no discernable mode in 2002 (Rayleigh Test, $Z = 0.15$, $P = 0.86$), but a mean direction of 305° ± 93.8° was detectable in 2003 (Rayleigh Test, $Z = 7.1$, $P < 0.001$), and a mean direction of 312° ± 96.9° was apparent in 2004 (Rayleigh Test, $Z = 3.5$, $P = 0.03$). These directions correspond to dates of November 6 and November 13 in 2003 and 2004, respectively, showing that the majority of DVCs occurred in November during 2003 and 2004 (Figure 2).

Discussion

Spatially, our High Precision model showed that DVCs had strong, positive correlation to speed limit, and this result was reinforced by the Hotspot analysis in which speed limit was the only correlate with the number of collisions reported from distinct intersections. These results may have occurred either because drivers of slower vehicles are more likely to detect a deer and are able to stop or swerve to avoid it or because DVCs tended to occur on the outskirts of the city where both deer populations and speed limits are high. Most previous studies of DVCs did not include traffic variables such as speed limit and traffic volume as variables (e.g., Finder et al. 1999, Hubbard et al. 2000, Madsen et al. 2002, Nielsen et al. 2003).

The 4 studies that did examine speed limit provided contradictory results (Allen and McCullough 1976, Bashore et al. 1985, Seiler 2005, Bissonette and Kassar 2008). Whereas Allen and McCullough (1976) found speed and collision rates to be positively correlated, Bashore et al. (1985) found the 2 variables to be negatively correlated. Seiler (2005) found a nonlinear effect that peaked at intermediate speed limits, possibly because deer avoided roads where vehicles moved at high speeds or because habitat variables were confounded with speed limits.

In the Edmonton area, reducing speed limits in the city periphery, where deer populations appear to be greatest, may be a low-cost way of reducing collision frequency. Speed limit reductions might be especially effective in areas where there are high amounts of nonforested green space and low densities of roads at times of the year when collisions are most likely or at intersections where higher numbers of collisions have occurred. Our results also underscore the importance of including traffic variables in analyses of DVCs.

A second variable, in addition to speed, that was important to our High Precision model was road density. Relative to random sites, DVCs were more likely to occur in areas with low road densities perhaps because many DVCs occurred in the outskirts of the city on freeways and township roads. These areas are typically surrounded by more deer habitat, including both forested areas used by deer for cover and nonforested areas, such as agriculture fields and wide roadside ditches that deer use for foraging. Freeways and township roads also typically reflect higher speed limits. Hence deer habitat and higher speed limits may be 2 variables that are confounded with road density. Nonetheless, our procedure for identifying correlated and confounding variables (see Methods) reduces the likelihood that these effects are actually more important than the combined interaction. Instead, road density may be the best indicator of deer habitat, and the high speed limits in those areas may additively contribute to the rate of DVCs.

Our High Precision model has 2 main limitations that could reduce the scope of its management implications. First, by referencing collisions to the nearest intersection, this database lacks precision at the outer edge of the city where roads are farther apart. We believe that our multiscale approach makes it less likely that this limitation introduced a systematic bias caused, for example, by failing to measure relevant habitat variables. However, that very feature introduced a second limitation, which is that our outermost habitat buffers sometimes overlapped, causing pseudo-replication of measured habitat variables. Because this was true of both collision and random locations, we think that this limitation, too, was unlikely to introduce systematic biases to our results. Despite the limitations of inaccuracy, sample size, and overlapping habitat measures, the logistic regression model produced by our study generated a good fit to the data, suggesting that it can provide some tools for managers and urban planners.

In the Edmonton area, reducing speed limits in the city periphery, where deer populations appear to be greatest, may be 1 low-cost way of reducing collision frequency. Speed limit reductions might be especially effective in areas where there are high amounts of non-forested green space and low densities of roads.

Our Aggregate model of collisions aggregated at the scale of township intersections revealed that DVCs were more likely to occur in areas near water. Although significant, the relationship between distance to nearest water and DVCs is weak, perhaps because there are abundant water sources interspersed through the city and surrounding areas. Nonetheless, proximity to water is important to deer because they require water to aid with digestion (Church 1993). In addition, riparian areas are generally more productive than surrounding areas and are likely to be used by deer for cover and forage. In this second analysis, road density alone was not a good predictor of DVC sites, but high road density combined with high vegetation productivity and high proportions of non-forested vegetation provided a better fit to the data.

The importance of proportion and productivity of vegetation to road density may explain why that variable predicted higher collision probabilities in the aggregate model. Road density alone predicted lower collision probabilities in the High Precision model. In many forest-dominated areas, productive non-forested vegetation is commonly found in the ditches alongside roads. Ditches are typically planted with introduced grasses that not only grow faster, but also green up faster than surrounding vegetation in the spring. In support of this interpretation, Bellis and Graves (1971) found that DVCs were strongly correlated with the number of deer seen grazing on planted right-of-ways, and Ramp et al. (2006) also found mammal fatalities were more likely to occur where roadside forage was abundant.

Another interpretation for the relationship between DVC density and both vegetation amount and productivity is that these conditions represent highway interchanges. To test this idea, we examined the 10 intersections that had the most DVCs in 2002, 2003, and 2004. We found that 7 of the 10 intersections were freeway interchanges and that they accounted for 13% of the collisions, suggesting that a large proportion of collisions occur at interchanges. Interchanges are typified by abundant planted grasses and higher use of salt in winter, which is a potentially important variable (Fraser and Thomas 1982) that we did not measure. In addition, interchanges contain high densities of roads in complex configurations that may confuse both deer and drivers. In support of this interpretation, Gavin and Komers (2006) found that areas with high road densities and high traffic volume produced conflict with pronghorn antelope (*Antilocapra americana*). The complex suite of road and vegetation factors found at highway interchanges may provide an additional explanation for the apparent contradiction in the effect of road density for the High Precision and the Aggregate models because the Aggregate model increased the relative weight of these sites, where as the High Precision model used more locations nearer the city core where road density was generally higher.

Temporally, DVCs were most likely to occur in November, and this supports previous studies (Bellis and Graves 1971, Allen and McCullough 1976, Madsen et al. 2002) that found that male deer mortality increased during the fall rut when boldness and movement of bucks increases (Allen and McCullough 1976, Madsen et al. 2002). Furthermore, the November peak overlaps with the fall hunting season, when hunters could potentially cause deer to move to local refugia (Conover 2001). A slight secondary peak in collisions occurred on about June 21, which may correspond to the time of the year when fawns begin moving with their mothers. These spring and fall peaks also coincide with increased mule deer movement as they migrate between summer and winter ranges (Conover 2002). The slight tendency for higher collision rates in spring might also be caused by the earlier green-up of the vegetation along road edges.

Management implications

Our results support 2 main implications for managers tasked with reducing the rate of DVCs. First, traffic speed was a significant variable in both the High Precision and the Hotspot models, suggesting that traffic speed is an important variable for predicting the locations of DVCs. It is surprising that only a few other studies have addressed this variable (Allen and McCullough 1976; Bashore et al.

1985, Bertwistle 2003, Seiler 2005, Ramp et al. 2006), and more research could reveal it to be a very important generalization for collision mitigation. If the importance of speed is robust, it could be an important tool for reducing DVCs, particularly in urbanizing areas where traffic volume is likely to increase (in this study, speed and volume were highly correlated).

A second implication of our study is that highway interchanges may generally possess the characteristics that correlate with higher rates of DVCs. More investigation of the complex mix of conditions at these sites is warranted, but interim solutions may be as simple as providing electronic signs at interchanges to slow drivers during peak seasons of DVCs to reduce driver habituation (Conover 2002, Sullivan et al. 2004). Photo radar might also be used to slow drivers rapidly and inexpensively.

Lastly, DVCs may be decreased by reducing the planting of palatable vegetation at highway interchanges and along rural roads generally. Because older vegetation becomes generally less palatable, reducing the frequency of mowing may also reduce forage value along existing roads (Conover 2002).

In addition to these 2 management implications, our study offers 3 important features that may be useful to other authors investigating the correlates of DVCs. First, the use of a standardized grid to identify collision locations in the aggregate analysis is readily transferable to other jurisdictions in North America that use a similar grid in both rural and urban contexts. This approach also lends itself well to multivariate statistics based on comparisons of collision and random sites (e.g., Finder et al. 1999, Hubbard et al. 2000, Nielsen et al. 2003, this study) that may generate more robust comparisons. Second, reporting the means and standard deviations of both collision and random sites (as we have done), will later make it possible to conduct meta-analyses of the most prevalent variables (Gurevitch and Hedges 1999). Vehicle speed is a prime candidate for this approach, and it will be important for other authors to report the magnitude of both significant and non-significant results. A third feature of our study that could be useful to managers elsewhere is the incorporation of several spatial scales in our analysis of local and landscape variables. Because deer respond to habitat at a variety of spatial scales that may differ with context (e.g., Kie et al. 2002), this use of multiple spatial scales may prevent failure to detect variables at one scale that are more apparent at another. Indeed, analyses that incorporate multiple spatial scales is a burgeoning topic in ecology (Boyce 2006), and multiscale approaches have been shown to be important for inclusion in habitat selection models of many ungulates (e.g., Ward and Saltz 1994; Schaefer and Messier 1995; Johnson et al. 2002*a*, 2002*b*).

In summary, subsequent studies that include traffic characteristics, employ multivariate statistics, examine variables at several spatial scales, and report both significant and non-significant effect sizes are likely to generate the kinds of generalizations that will make it possible to reduce DVCs in future. This effort is well-justified because DVCs are steadily increasing in many parts of the world (Jensen 1995, Groot Bruinderink and Hazebroek 1996, Romin and Bissonette 1996), and the danger they pose to human health and property will certainly increase dramatically in the coming decades.

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