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Predicting deer–vehicle collisions in an urban area

Rob Found*, Mark S. Boyce

Department of Biological Sciences, University of Alberta, CW-405, Biological Sciences Building, Edmonton, AB T6G 2E9, Canada

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ABSTRACT

Collisions with deer and other large animals are increasing, and the resulting economic costs and risks to public safety have made mitigation measures a priority for both city and wildlife managers. We created landscape models to describe and predict deer–vehicle collision (DVCs) within the City of Edmonton, Alberta. Models based on roadside characteristics revealed that DVCs occurred frequently where roadside vegetation was both denser and more diverse, and that DVCs were more likely to occur when the groomed width of roadside right-of-ways was smaller. No DVCs occurred where the width of the vegetation-free or manicured roadside buffer was greater than 40 m. Landscape-based models showed that DVCs were more likely in more heterogeneous landscapes where road densities were lower and speed limits were higher, and where non-forested vegetation such as farmland was in closer proximity to larger tracts of forest. These models can help wildlife and transportation managers to identify locations of high collision frequency for mitigation. Modifying certain landscape and roadside habitats can be an effective way to reduce deer–vehicle collisions.

1. Introduction

Increases in deer–vehicle collision (DVCs) in North America and Europe have been linked to rising populations of both humans and deer (Putman, 1997; Hussein et al., 2007; Morellet et al., 2007). Human-disturbed landscapes, such as where urban or agricultural developments are adjacent to forested areas, create heterogeneous and fragmented habitats preferred by deer (Stewart et al., 2000). Spreading urban development is, therefore, increasing deer–human encounters, of which deer–vehicle collisions are the most costly (Huijser et al., 2009). Property damage from ungulate collisions is estimated to be almost $300 million/year in Canada and over $6 billion/year in the USA, with 90% of DVCs ending in deer fatalities, and 56–65% ending in human injury (Huijser et al., 2009; Transport Canada, 2003; Conover et al., 1995).

Of transportation agencies surveyed across Canada and the USA, 77% rarely or never employ wildlife-collision mitigation strategies during planning or construction of roads (Kociolek and Clevenger, 2007). When mitigation measures are put into place, they are usually selected and located arbitrarily (Putman, 1997). Historical trends in DVC locations can be useful, although only 30% of jurisdictions in the USA actually maintain DVC data (Sullivan and Messmer, 2003). Reliable and effective methods of predicting and mitigating DVCs have become a priority for a diverse group of planners and managers (Farrell and Tappe, 2007). The combinations of wildlife crossing structures and exclusion fencing have been most successful at reducing DVCs, but these methods also are the most expensive (Tardif, 2003; Dodd et al., 2007). Developing statistical models to predict DVC locations can help to identify the highest risk areas for mitigation, and thus increase their cost effectiveness.

In previous studies, researchers have found correlations between DVC frequency and a number of landscape and traffic variables. Deer choose clearings with adjacent wooded areas over entirely wooded areas, which might explain deer attraction to right-of-way habitats created by roadways (Stewart et al., 2007; Farrell and Tappe, 2007). The presence of open ground near wooded areas, higher vehicle speeds and traffic volume, nearby water, and proximity to highly productive non-forested vegetation have been correlated with higher DVC frequencies, whereas higher road densities and the presence of fencing and buildings were inversely correlated (Bashore et al., 1985; Nielsen et al., 2003; Ng

* Corresponding author. Tel.: +1 780 492 0081; fax: +1 780 492 9234.
E-mail address: found@ualberta.ca (R. Found).

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et al., 2008; McShea et al., 2008). Because only Nielsen et al. (2003) and Ng et al. (2008) used urban study areas, the landscape factors behind DVCs are still not completely understood. Site-based habitat characteristics at the roadside might provide us with the most practical management options for mitigation through habitat modification. While Malo et al. (2004) studied roadside factors affecting DVC risk, few previous studies have examined site-based roadside factors predicting deer–vehicle collisions.

We used Geographic Information Systems (GIS) to map yearly DVC data within the city limits of Edmonton, Alberta to identify locations of high-DVC frequency. For 2 landscape models, we hypothesized that coarse-scale factors describing deer habitat selection would reflect factors predicting DVC locations and frequencies. Based on previous studies of the ecology of deer we predicted that deer would select heterogeneous landscapes where both forested and non-forested vegetation are available in proximity to each other, and that deer would avoid areas with fencing and buildings. We also estimated a model in which we hypothesized that more DVCs would occur where roadside vegetation both attracted deer near to the road and increased the risk of a collision because of decreased visibility to drivers. With this project we aim to furnish planning and managing agencies with tools for predicting where DVCs will occur, and where preventative and mitigating measures such as wildlife crossing structures and roadside fencing might be constructed. Our roadside-based models also suggest that roads and roadsides themselves might be modified to mitigate DVCs.

2. Study area

Our study area was the City of Edmonton, Alberta, and a 1-km buffer around the outside of the city boundaries. Edmonton is undergoing rapid growth, as reflected by expanding suburban housing projects and increased road construction. This city of >1 million people is located in the aspen (*Populus tremuloides*) parkland ecoregion of Canada. The North Saskatchewan River bisects the city diagonally, and including side ravines forms a 7400-ha river valley parks system that is one of the largest continuous urban parks in North America (City of Edmonton, 2009). The river valley is vegetated with aspen, poplar (*Populus* spp.) and spruce (*Picea* spp.) forests, shrubs, and open vegetated spaces that include both manicured recreational lands and meadows. Fringing areas on either side of the city boundary are agricultural fields, rural residential properties, wetlands, and stands of mixed forest. These landscape conditions create a heterogeneous landscape that provides deer with prime habitat: dense forests containing both browse and cover in close proximity to open vegetated areas rich in nutritious grasses, forbs, and planted crops. Winters are long and often harsh with an average of 121 days with snow-covered ground, whereas summers are warm and mostly sunny. Annual average temperature is 1.8 °C, and average snowfall is 130 cm (City of Edmonton, 2009).

3. Methods

3.1. Collision data

Data for deer–vehicle collisions from 2002 to 2007 were based on the number and location of roadside or on-road deer carcasses collected within the Edmonton city boundaries (S. Exner, Edmonton Animal Control Services, personal communication). These data include the locations of carcasses to the nearest intersection of any two roads, as described by the numbered street and address grid system used within the city limits. These locations were converted to Global Positioning System (GPS) coordinates for analysis (Fig. 1). We estimated the recorded carcass locations to be within 400 m of the actual carcass location, and to account for further location discrepancies introduced when deer–vehicle collisions are not immediately fatal and the deer is able to move off some distance before dying, we defined DVC locations as non-overlapping 800 m radius buffers around each street intersection, where each DVC could only be assigned to the buffer around a single street intersection. We assumed that each carcass was the result of a DVC. Previous research has estimated that approximately 90% of all deer–vehicle collisions result in deer fatalities, so we presumed that retrieved deer carcasses were equally representative of deer–vehicle collisions, and we assumed that carcass retrieval data were synonymous with DVC data (Allen and McCullough, 1976; Transport Canada, 2003). We did not record carcass sex and species, and although most road-killed deer were white-tailed deer (*Odocoileus virginianus*), the occasional mule deer (*Odocoileus hemionus*) might have been included in the data (S. Exner, Edmonton Animal Control Services, personal communication).

3.2. Roadsides model

We used the 2002–2007 carcass data to identify 26 locations of high DVC frequency, which we termed "hotspots". We defined a DVC hotspot to be the area within an 800-m radius around a street address location, to the nearest intersection, from which carcasses were retrieved in at least 1/2 of the recorded years, and multiple carcasses retrieved in at least 1 of the years. We used these criteria to ensure that a hotspot was defined partly by a year-to-year pattern of DVCs, and to avoid using locations where there were only 1 or 2 anomalous years with DVCs. Using more strict criteria would have resulted in too small a sample size, while using less strict criteria would have resulted in too many locations for them to be considered targeting "hotspots" from a management perspective. Also, using our criteria, there were no hotspots that had overlapping 800 m buffers.

For analysis we matched these hotspots to 26 DVC "coldspots" of 800 m radii around street intersections with very low DVC frequencies. Coldspots were defined to be locations with ≤ 1 carcass, in total, retrieved over the most recent three years of data (2005–2007), ≤ 2 total carcasses over the six years of data (2002–2007), and no single year with multiple carcass retrievals. The criteria for matching cold and hotspots were: similar road orientation (north–south, east–west, or diagonally), average 2004–2007 traffic volumes (from City of Edmonton daily vehicle counts) that differed by no more than 25%, and posted speed limits that varied no more than 10 km/h (City of Edmonton, 2007a). We divided the City of Edmonton into regions defined by several major, multi-lane north–south and east–west roads, and all matched cold/hot spots were found in the same region within the city. We based traffic volume tolerances on yearly variation ranging up to 25% at many locations. We based speed limit tolerances on assumptions that actual vehicle speeds often differ from posted speed limits by up to 10 km/h (Allen and McCullough, 1976).

We recorded and derived a total of 21 variables describing roadside habitat and roadway characteristics around each hotspot and coldspot. Variables were chosen based on hypothesized biological relevance and their potential to influence DVC frequency as determined by a literature review. Vegetation data for the 800 m radius buffers were gathered from 80×2 m strip transects perpendicular to each side of the roadway, every 200 m. We categorized vegetation and landcover as either water (of any sized body), non-vegetated (pavement, naked soil, etc.), leaf litter, manicured grass, non-manicured grass, agricultural crops, shrubs, and deciduous or coniferous trees with any previous category as an understory. We estimated the proportion of each vegetation type within the 2 m wide transect at 10 m intervals along each transect.

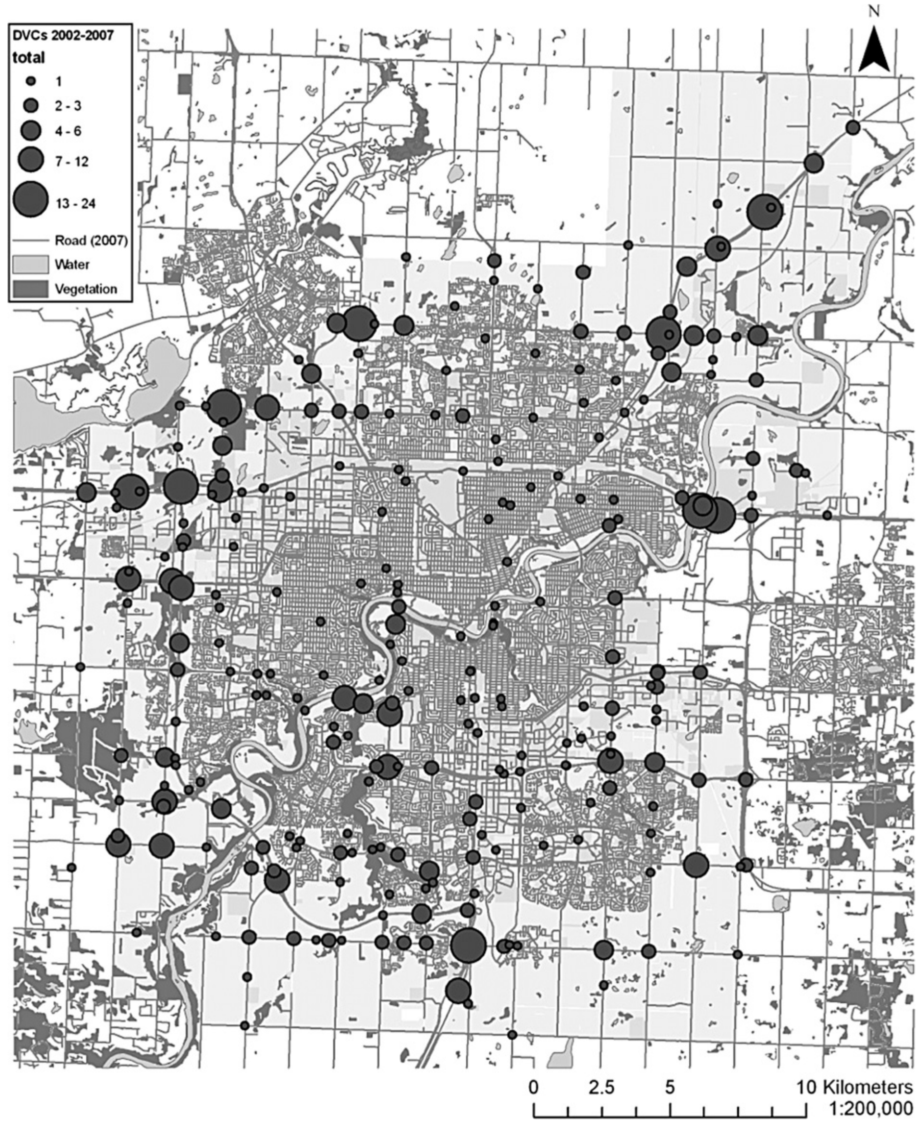

Fig. 1. Frequencies and locations of all deer–vehicle collisions within Edmonton, AB (shaded light grey), from 2002 to 2007. Based on deer (*Odocoileus* spp.) carcasses picked up by city Animal Control Services. Locations are to nearest actual or estimated street address. Size of circles increases with the number of collisions at that location. Road, water, and vegetation data were from 2007.

We estimated the percentage of canopy cover by spotting through a 5-cm diameter cylinder held at eye level, at the midpoint of each 10-m section. We used a Robel pole to estimate vegetation height and density at the 30 m mark of each transect, and recording average of measurements from each of 4 quadrants around the pole (Robel et al., 1970). Where transects were interrupted by fencing 2.4 m or higher, we labeled the remaining distance "limited access." Where a transect was interrupted by a building or other feature that similarly prevented deer from occupying the area, we labeled the remaining distance "unusable." Groomed width was the distance from the edge of the pavement defining the road to the nearest distance along each transect where the vegetation was not mowed or otherwise manicured. Groomed width, therefore, includes mowed grass, but also any length of transect next to the road that had no vegetation (e.g., parking lot or non-cultivated dirt). Distance to bush was from roadside to nearest woody vegetation. We calculated vegetation diversity using the Shannon index based on the proportions of vegetation type at each hot or coldspot. We averaged data from the 16 transects surrounding each hot or coldspot to yield single defining variables for each individual location. A single observer gathered all field data from June through November of 2008. This period was bounded by the two seasonal peaks in DVC; more DVCs occurred in these 2 months than in any of the other 10 months of the year (Found and Boyce, in press).

When roadside variables were correlated with $|r| > 0.7$, only the variable with the lowest *P*-value in single-variable tests was included in the model. We included only those covariates with main effects identified as liberally significant ($P \leq 0.25$) with univariate tests. Only ecologically plausible combinations of covariates and selected interactions were included together in a model. We used conditional (matched-case) logistic regression to build the models, and used Akaike's Information Criterion (corrected AIC_c) to select the best model, which we called the "Roadside Model." Statistical calculations were performed using STATA 9.1 (College Station, Texas). As a measure of each model's performance in differentiating hotspots from coldspots, we used Nagelkerke's generalized R^2 to calculate how much of the variation in the data is attributed to the model. By using this metric we do not imply that statistical inferences should be made using these reported R^2 values.

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3.3. Landscape-based models

To model DVC locations at a broader scale and at resolutions attainable with most government GIS data sets, we created 2 "landscape" models. We developed 2 landscape-based models that extended beyond city limits by combining municipal and provincial data at 1:20,000 scale to produce a combined map of the study area (City of Edmonton, 2003, 2007b). We then reclassified the landcover and landuse zones into 5 discrete and ecologically relevant landcover classes following Ng et al. (2008): (1) urban residential, comprised of both high- and low-density housing; (2) urban non-residential, describing industrial and business zones; (3) non-forested vegetation, which includes agricultural land, meadows, and recreational open space; (4) forested vegetation, including all woody vegetation; and (5) water, comprising all mapped and permanent bodies of water. We obtained data on landcover variables from non-overlapping 800-m buffers created around each 2002–2007 DVC location ($n = 260$), and each of 260 locations with no recorded DVCs. These control sites were generated randomly along the 2007 digital road layer using GIS non-overlapping neighborhood statistics, selecting only from roadway intersections, or at 1600-m intervals along stretches of roadway with no intersections. This was necessary to match the methods used to identify carcass locations so that neighborhood statistics were generated only from locations where carcass locations potentially could have been identified. The 1600-m interval was used because it aligns with the road grid system used throughout our study area and throughout Canada and many parts of the United States, in which road right-of-ways are designated every 1.6 km or 3.2 km.

Variables derived from the landcover classes included the proportion of landcover type within each 800-m buffer, the distance from the buffer's centroid to the nearest patch of each landcover type, and the edge density of each landcover class within each buffer. Remaining landscape variables included road density in each buffer, change in road density (from 2003 to 2007), and posted speed limit. Traffic volume data were not available for many locations, so this variable was not included in landscape models. Where available, traffic volume was highly correlated with speed limit, and because speed limit is more easily manipulated by managers than traffic volume, we felt speed limit was a superior variable to include in alternative models. To avoid collinearity we removed 1 of 2 predictor variables that were correlated with $|r| > 0.7$, and used the 16 remaining variables to develop 2 landscape-scale models.

We used logistic regression to contrast DVC locations versus non-DVC locations to construct a "location model" (SYSTAT 12, San Jose, CA). We used the frequency of DVCs at each DVC location as the dependent variable to construct a landscape-based "frequency model". For this frequency model we used zero-truncated negative binomial regression to fit a negative binomial distribution to counts of DVCs at locations with at least 1 DVC, and thus no zeros in the data. Model building followed the information-theoretic strategy as used for the roadside-based model, and we again used AIC_c to select each of the best location and frequency models. Model performance was evaluated using Nagelkerke's generalized R^2 to estimate how much of the variation in the data is attributed to the model, again recognizing that statistical inferences should not be made based on the reported R^2 values.

Table 1
Roadside variables differing significantly ($P < 0.05$) between 26 deer–vehicle collision hotspots and 26 deer–vehicle collision coldspots, using 2-sample t-tests of the means. Data gathered during 2008 in Edmonton, AB.

Variable	Hotspots		Coldspots		P[e]	t_{50}
	Mean	SE	Mean	SE		
Groomed width (m)	8.5	1.87	32.0	3.92	<0.001	−5.41
Vegetation density[a]	10.1	0.79	4.9	0.66	<0.001	5.13
Vegetation diversity[b]	1.41	0.071	1.20	0.068	0.017	2.18
Accessible habitat[c]	0.90	0.027	0.71	0.050	<0.001	3.26
Subsidiary roads[d]	4.0	0.37	6.5	0.94	0.007	−2.51

[a] Height (cm) of lowest Robel pole band visible through vegetation.
[b] Shannon diversity index score.
[c] Proportion of habitat not blocked by buildings or fencing greater than 7.5 m.
[d] Number of roads of any type feeding into the main road of the hotspot or coldspot.
[e] One-tailed results.

Table 2
Candidate roadside models predicting deer–vehicle collision hotspots in Edmonton, Albert, AB, using 2008 field data for 26 matched-cases. Hotspots and coldspots were matched using traffic volume and speed limits and models estimated using matched-case logistic regression. Models ranked by Akaike Information Criteria (AIC_c) with correction for small sample size. R^2 is Nagelkerke's generalized R^2.

Model	AIC_c	Δ_i[a]	K[b]	ω_I	R^2
Groomed width + vegetation density + distance to woody vegetation	40.354	0	4	0.583	0.722
Groomed width + vegetation density + vegetation diversity × distance to woody vegetation	41.183	0.8	4	0.391	0.713
Groomed width + vegetation density	46.659	6.3	3	0.025	0.612
Groomed width	52.413	12.1	2	0.001	0.492

[a] AIC_c-minimum AIC_c.
[b] Number of estimable parameters.

4. Results

4.1. Roadsides models

The means of 5 of the 18 non-correlated variables differed significantly ($\alpha = 0.05$) between hotspots and coldspots (Table 1). Groomed widths were 73% smaller at hotspots than at coldspots (vegetation density was 52% greater at hotspots than at coldspots). Vegetation diversity (Shannon index) was greater at hotspots than at coldspots. The proportion of deer-accessible habitat was 21% greater at hotspots than at coldspots, and there were 38% fewer subsidiary roads feeding into the main signed roads at hotspots ($\bar{x} = 4.0$ roads) than at coldspots.

Our Roadsides model predicted that hotspots were more likely to occur where groomed width was smaller, roadside vegetation was denser, and the interaction between vegetation diversity and distance to nearest woody vegetation was increasing (Tables 2 and 3).

4.2. Landscape-based models

The means of 14 of the 16 non-correlated variables differed significantly ($P < 0.05$) between the 260 DVC locations and the 260

Table 3
Coefficients, standard errors, and 95% confidence intervals for the selected roadside-based model, from candidate roadside models predicting deer–vehicle collision hotspots in Edmonton, Alberta. Model constructed using 2008 field data from 16, 80-m-long transects perpendicular to each of 26 "hotspots" of high DVC frequency, and 26 matching DVC "coldspots". Hotspots and coldspots were matched using traffic volume and speed limits and models were estimated using matched-case logistic regression.

Parameter	β	SE	95% CI
Groomed width[a]	−0.079	0.032	−0.141 to −0.017
Vegetation density[b]	0.573	0.195	0.191–0.955
Distance to woody vegetation[c]	0.099	0.040	0.0200–0.178

[a] Distance in meters of roadside right-of-way.
[b] Number of the lowest 5-cm wide Robel pole band visible through vegetation, 30 m from roadside.
[c] Distance in meters from road.

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Table 4
Means and test statistics for landscape variables differing significantly between deer–vehicle collision (DVCs) locations and random null sites, within the City of Edmonton, Alberta in 2007. Data were extracted from 800 m buffers surrounding 260 DVC sites, and 260 non-DVC sites.

Variable	Mean	Values	t_{518}	P
	DVC	Non-DVC		
Speed (km/h)	69.2	55.5	−12.579	≤0.001
Landcover heterogeneity[a]	3.87	3.58	−4.032	≤0.001
Forested vegetation[b]	0.061	0.018	−6.548	≤0.001
Non-forest vegetation[b]	0.516	0.206	−13.847	≤0.001
Urban non-residential[b]	0.179	0.256	4.239	≤0.001
Urban residential[b]	0.226	0.511	13.821	≤0.001
Distance to water[c]	616.0	1075.5	7.337	≤0.001
Distance to forest[c]	767.9	1252.8	6.754	≤0.001
Distance to non-forest vegetation[c]	19.4	75.4	9.671	≤0.001
Distance to residential[c]	275.9	56.6	−7.369	≤0.001
Distance to urban[c]	94.9	4.2	−6.030	≤0.001
Water edge[d]	1462.3	596.9	−7.898	≤0.001
Forest edge[d]	1914.8	734.3	−6.903	≤0.001
Roads[d]	14,149.6	22,917.9	13.325	≤0.001

[a] Number of landcover classes, out of 5, represented within the buffer.
[b] Proportion of buffer covered by listed landcover class.
[c] Distance (m) from centroid of buffer to nearest patch of listed landcover class.
[d] Total linear distance (m) within buffer.

non-DVC locations (Table 4). Of these variables, 6 were incorporated into 1 or both of the landscape models. Posted road speed limits were 25% higher at DVC locations (Table 4). Non-DVC locations were 289% farther from non-forested vegetation than DVC locations. Within the 800-m buffers the proportion of forested vegetation was 239% more and the proportion of non-forested vegetation was 150% more at the DVC locations than at non-DVC locations. Road density was 62% higher at non-DVC locations (Table 4). Landscape heterogeneity (i.e., land classes/buffer) was 8% higher at DVC locations.

Our landscape-based "location" model predicted that DVCs were more likely to occur at locations where the speed limit was higher, where there was more total vegetation (both forest and non-forest), and where the interaction between the amount of forest and the distance to the nearest non-forested vegetation was decreasing (Tables 5 and 7). Our landscape-based "frequency" model predicted that a higher frequency of DVC was expected where the speed limit was higher, the distance to the nearest non-forested vegetation was shorter, the landscape was more heterogeneous, and the road density is lower (Tables 6 and 7). Using ArcGIS focal functions, we applied both models to an 800-m radius window moving cell-by-cell throughout the study area, and from it generated a map showing the relative frequency of DVCs expected at any location within our study area (Fig. 2). Moving window calculations also allowed prediction of DVCs along potential future roadways.

Table 5
Candidate landscape-based models predicting deer–vehicle collision (DVC) locations in Edmonton, Alberta, using 2007 GIS data for 260 unique DVC locations and 260 random control sites. Models were estimated using logistic regression and ranked by Akaike Information Criteria (AIC_c). Delta is the difference between the top model and each candidate model, K is the number of estimable parameters and ω is the relative weighting of that model. R^2 is Nagelkerke's generalized R^2.

Location models	AIC_c	Δ_i[a]	K[b]	ω_I	R^2
Speed + forest + non-forested vegetation + forest × distance to non-forested vegetation	490.94	0	5	0.630	0.493
Non-forested vegetation + speed + forest × speed + urban non-residential	493.00	2.1	5	0.220	0.489
Non-forested vegetation + speed + forest × speed + distance to non-forested vegetation	493.98	3.0	5	0.141	0.488
Non-forested vegetation + speed + forest × speed	499.67	8.7	4	0.008	0.475
Non-forested vegetation + speed + forest edge density	503.59	12.7	4	0.001	0.469
Non-forested vegetation + road density + speed	525.12	34.2	4	0.000	0.432
Non-forested vegetation + speed	530.35	39.4	3	0.000	0.420
Forest edge density + residential + speed × road density	542.56	51.6	4	0.000	0.379
Non-forested vegetation	567.03	76.1	2	0.000	0.349
Speed	622.26	131.3	2	0.000	0.328

[a] AIC-minimum.
[b] Number of estimable parameters.

Table 6
Candidate landscape-based models predicting deer–vehicle collision (DVC) frequencies in Edmonton, Alberta, using 2007 GIS data for 260 DVC locations. Models estimated using zero-truncated negative binomial regression, and ranked by Akaike Information Criteria (AIC_c). Delta is the difference between the top model and each candidate model, K is the number of estimable parameters and ω is the relative weighting of that model.

Frequency models	AIC_c	Δ_i[a]	K[b]	ω_I	R^2
Speed + landcover heterogeneity + non-forested vegetation	722.46	0	4	0.825	0.651
Speed + landcover heterogeneity + distance to non-forested vegetation + road density	725.64	3.1	5	0.175	0.299
Speed + non-forested vegetation	738.50	16.0	3	0.000	0.261
Non-forested vegetation + landcover heterogeneity	744.40	21.9	3	0.000	0.243
Speed + landcover heterogeneity	744.67	23.2	3	0.000	0.242
Speed	756.92	34.4	2	0.000	0.204
Non-forested vegetation	763.55	41.0	2	0.000	0.182

[a] AIC-minimum AIC.
[b] Number of estimable parameters.

5. Discussion

Our 3 DVC models showed that deer–vehicle collisions are predicted by a combination of habitat variables that describe areas attractive to deer, and roadway variables that increase the risk that a crossing deer will be hit. DVC risk has been linked to deer habitat selection in previous studies (Hubbard et al., 2000; Nielsen et al., 2003; Ng et al., 2008; Farrell and Tappe, 2007). Deer are both browsers and grazers that will forage in both open and forested areas, and juxtaposition of open and forest is expected to draw

Table 7
Parameters in highest-ranking landscape models for deer–vehicle collision (DVC) locations and frequencies. Data 2007 were collected during 2007 from 800 m buffers around 260 deer–vehicle location (location and frequency models) and 260 random null sites (location model only) within the City of Edmonton, Alberta.

Parameter	β	SE	95% CI
Location model[a]			
Speed limit	0.069	0.013	0.043–0.094
Forest	14.650	2.893	8.981–20.320
Non-forest vegetation	2.555	0.482	1.611–3.499
Forest × distance to non-forest vegetation.	−0.185	0.070	−0.323 to −0.047
Frequency model[b]			
Speed limit	0.049	0.011	0.027–0.071
Non-forested vegetation	2.536	0.556	1.446–3.626
Landcover heterogeneity	0.680	0.170	0.346–1.013

[a] Modeling locations that have DVC.
[b] Modeling the frequency of DVC at each location.

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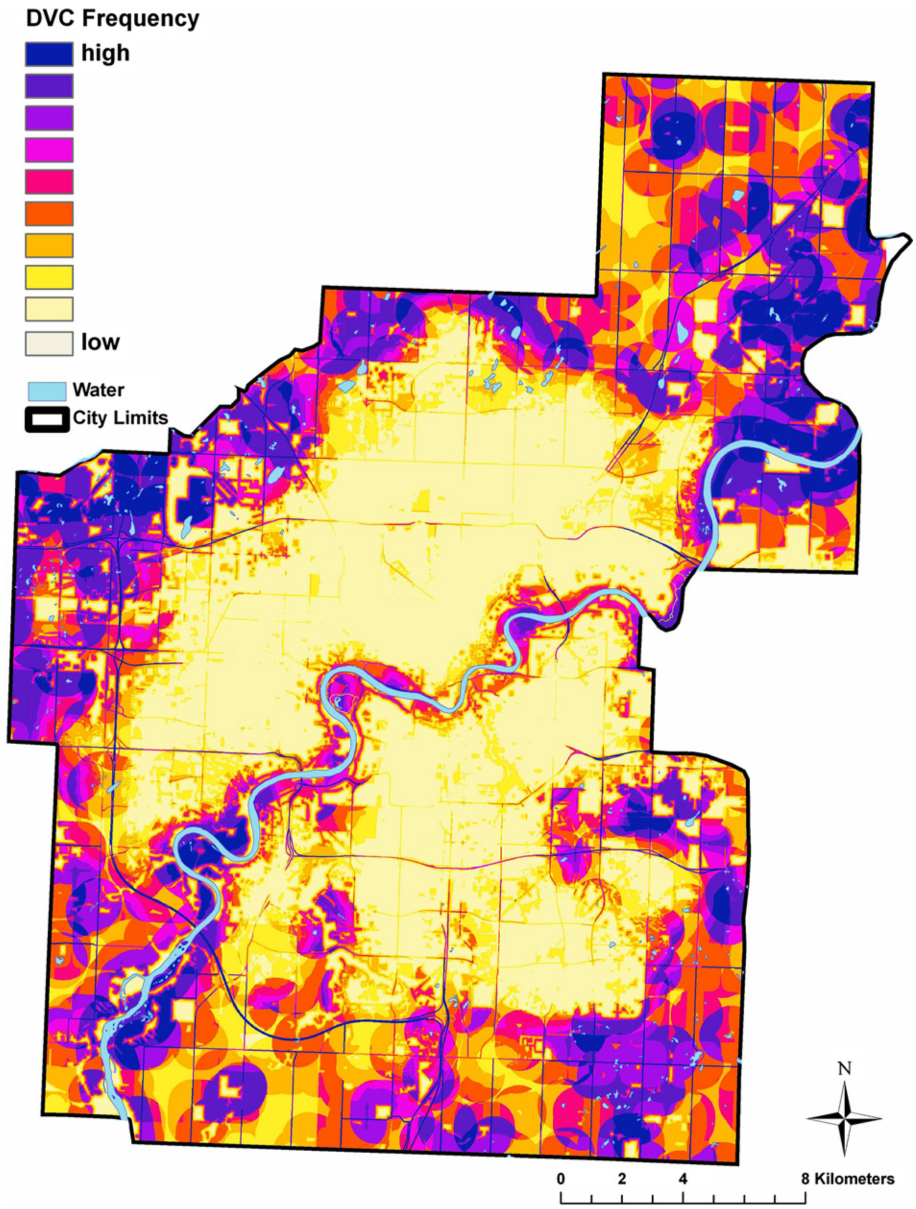

Fig. 2. Map predicting where deer–vehicle collision frequencies are expected to be highest, within Edmonton, Alberta. Landscape variables from digital 2003 and 2007 data were extracted from 800 m buffers around 260 known deer–vehicle collision locations weighted by the number of deer–vehicle collisions recorded there from 2002 to 2007, based on model estimated using zero-truncated negative binomial regression. Higher frequencies of deer–vehicle collision expected to occur where posted speed limits are higher, the distance to the nearest non-forested vegetation is less, the density of roads within the buffer is less, and the number of different landcover classes represented in each buffer is greater (a measure of landscape heterogeneity).

more deer (Bramble and Byrnes, 1979; Vangilder et al., 1982). Previous studies have found that high density of edge habitat between forest and fields or pastures, and also decreasing distance to forest, increase the risk of a DVC (Farrell and Tappe, 2007; Tappe and Enderle, 2007). The proximity requirement between forest and non-forested vegetation was seen in the interaction parameter in our Location model, whereas our Frequency model predicted higher DVC frequency when the amount of available non-forested vegetation was greater. This aligns with Ditchkoff and Servello (1998) and Bashore et al. (1985) who found that although deer selected open areas for grazing, they selected foraging areas with nearby forest that they used for cover, bedsites, and additional food sources such as browse and even leaf-fall. Diverse habitat requirements for foraging and predator avoidance lead deer to select more heterogenous landscapes.

In our top 2 landscape-based Frequency models landcover heterogeneity was positively associated with the probability of DVCs. A prior study found that increased forest contrast was a major predictor of DVCs (Farrell and Tappe, 2007), and it is well documented that white-tailed deer prefer heterogeneous landscapes (Storm et al., 2006). Premo and Rogers (2001) found that DVCs increased in areas of urban expansion, and our Frequency model showed DVCs were more likely in suburban areas of lower road density surrounding urban areas. As also found by Ng et al. (2008), vehicle speed limits are a prime predictor of DVCs, and while roads with high speed limits occurred in both high and low road density areas, areas with high vehicle speeds and low road density are most commonly found in the suburban fringe around Edmonton. Also, this suburban area had more forest and meadows than more urban areas. Most locations of high DVC frequency occurred in these areas (Fig. 1).

Habitats that deer prefer are common along many of our roadways and roadway planners typically maintain a non-forested buffer along roadways. These buffers are often bordered by forest and other woody vegetation. The most significant roadside predictor of DVCs was the groomed width of these non-forested buffers. Groomed width was inversely correlated with average canopy cover along the transect, and both reflect proximity to forest. This supports research that found DVCs increased with declining distance to adjacent forest cover (Finder et al., 1999). During dawn and dusk deer leave forest cover to feed and select adjacent open areas where predator detection is easier, and where easily digestible forbs, grasses, or commercial crops can be accessed (Vangilder et al., 1982; Stewart et al., 2007). This can bring deer into roadside right-of-ways at precisely the time when visibility for drivers is worst. This visibility is further compromised when the roadside vegetation is particularly dense, and deer near the road but not fully within the open areas of the right-of-way can remain unseen by drivers. Our Roadsides Model supported this, predicting more DVC hotspots where roadside vegetation density was higher, regardless of the groomed width of the right-of-way.

All 3 models suggest that landscape and roadside habitat modifications have the potential to mitigate DVCs. Grooming of roadside right-of-ways allows roadside animals to be more easily seen by drivers, and our results indicate that increasing the width of these groomed right-of-ways could yield reductions in DVCs. Not one of our DVC hotspots had a groomed width greater than 40 m, and we suggest that ensuring at least 40 m groomed roadsides has the potential to reduce DVCs markedly. This is similar to models by Malo et al. (2004) that predicted higher wildlife–vehicle collision risk along sections of roads where there was woodland or hedges near to the road. Maintaining a 40–80-m roadside buffer within which vegetation is either absent or vigilantly manicured also would suppress vegetation diversity and limit vegetation density. These modifications might reduce the attraction of roadsides to deer, and eliminate deer bedsites and fawn hiding spots close to roads. Where trees remain within roadside buffers, secondary shrubbery underneath the canopy should be removed. Such modifications would logically extend to removal of trees within the 40–80 m roadside buffer, but where roads pass alongside croplands that require trees as windbreaks to prevent topsoil erosion the installation of deer-proof fencing might be considered as a costly but effective option. While our models are specific to the habitat choices of white-tailed and mule deer, many of these roadside modifications could reduce collisions with other wildlife and even livestock at-large.

Roadways themselves can be manipulated to yield reductions in DVCs. New roads could be routed to avoid areas that would require extensive habitat modification in the first place, and avoid areas where high-DVC risk would be expected. Where new roads must travel through high-risk areas, mitigation techniques such as wildlife under and overpasses and roadside exclusionary fencing can be placed more effectively by knowing where DVC risks are highest. Finally, while it might be unrealistic to expect road density to be manipulated to reduce DVCs, our models suggest that simply reducing speed limits on roads traveling through high DVC-risk areas could lead to a reduction in DVCs. Using signs to warn drivers of potential DVCs can have the indirect effect of reducing driver speeds in high-risk areas. Pojar et al. (1975) showed that lighted and animated deer-crossing signs reduced driving speeds by 5 km/h, while Found and Boyce (in press) showed that warning signs targeting DVC hotspots reduced collisions by 34%. Permanent reductions in posted speed limits also has been shown to reduce vehicle collision rates with both bighorn sheep (*Ovis canadensis*) and elk (*Cervus elaphus*) (Bertwhistle, 1999).

The similarity of our models to those developed by Malo et al. (2004) for roe deer (*Capreolus capreolus*) and red deer (*C. elaphus*) in Europe suggest that while local species variation in habitat selection might dictate specifics, management practices suggested here might be applied in any jurisdiction where deer–vehicle collisions occur.

5.1. Conclusions

Our results suggest that historical DVC data can be used to identify DVC hotspots for mitigation. Modeling these historical DVCs on both the landscape and roadsides presents a number of management options. Our results showed that simple roadside habitat modifications could effectively reduce DVCs along existing roadways. Our results also show how DVC modeling could help direct the planning of future roadways so that high-DVC-risk locations might be minimized from the start. Transportation planners also should consider the landscape patterns behind DVCs when roads must be built through areas of high DVC risk. More precise identification of high-risk areas will result in more cost-effective installation of successful but expensive mitigation such as wildlife crossing structures and roadside exclusionary fencing (Clevenger et al., 2001). The rising tide of wildlife–vehicle collisions and urbanization around the world only will increase the importance of these management implications.

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