Journal of Applied Ecology 2005
42, 371–382

Predicting locations of moose–vehicle collisions in Sweden

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Summary

1. Animal–vehicle collisions are a serious problem for road planners and biologists concerned with traffic safety, species conservation and animal welfare. In Sweden, vehicle collisions with moose (MVC) are an important safety issue. Police records average approximately 4500 incidents year^{-1}, including 10–15 human fatalities. New mitigation policies require improved knowledge of the factors influencing the spatial distribution of MVC.

2. Three logistic regression models were developed to predict MVC risks on public roads for use in strategic and project-related impact assessment. The models were based on remotely sensed landscape data, road and traffic statistics and estimations of moose density, quantified at 2000 accident and 2000 non-accident control sites in south-central Sweden. Model predictions were validated on 2600 1-km road sections in the county of Örebro, which were classified as either accident or non-accident roads. Model performances were compared using Akaike's information criterion.

3. Traffic volume, vehicle speed and the occurrence of fences were dominant factors determining MVC risks, identifying 72·7% of all accident sites. Within a given road category, however, the amount of and distance to forest cover, density of intersections between forest edges, private roads and the main accident road, and moose abundance indexed by harvest statistics, significantly distinguished between accident and control sites. In combination, road–traffic and landscape parameters produced an overall concordance in 83·6% of the predicted sites and identified 76·1% of all test road sections correctly.

4. *Synthesis and applications*. The risk of moose–vehicle collisions in Sweden can be predicted from remotely sensed landscape data in combination with road traffic data. Prediction models suggest that reduced vehicle speed in combination with road fencing and increased roadside clearance may provide effective tools for road planners in counteracting MVC. However, effective mitigation will depend on integrated management of the surrounding landscape and moose population, as well as increased responsibility of individual drivers. Remedying animal–vehicle collisions must involve road authorities as much as landowners and the public.

Key-words: accidents, *Alces alces*, fences, mitigation, road casualties, roads, traffic safety

Journal of Applied Ecology (2005) **42**, 371–382
doi: 10.1111/j.1365-2664.2005.01013.x

Introduction

Collisions between ungulates and motor vehicles are considered to be an increasing threat to traffic safety, socio-economics, animal welfare, wildlife management and conservation in many countries world-wide (Child & Stuart 1987; Lavsund & Sandegren 1991; Groot-Bruinderink & Hazebroek 1996; Romin & Bissonette 1996; Schwabe, Schuhmann & Tonkovich 2002). In Sweden, ungulate–vehicle collisions have multiplied over the past 30 years in response to increased traffic and greater numbers of ungulates (Seiler 2004). During the 1990s, up to 5000 moose *Alces alces* L. and 25 000 roe deer *Capreolus capreolus* L. were reportedly involved in collisions with vehicles each year, accounting for

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more than 60% of all police-reported road accidents (Swedish National Road Administration, SNRA, Borlänge, Sweden). However, as not all collisions are detected by the drivers, reported to the police or registered by the SNRA, the actual number of collisions with ungulates is probably more than twice as high (Almkvist *et al.* 1980). A recent survey of drivers suggested that the true number of collisions probably exceeds 10 000 incidents with moose and 51 000 incidents with roe deer annually (Seiler, Helldin & Seiler 2004).

Accidents with moose are a great threat to traffic safety. They comprise up to 80% of all animal-related vehicle collisions that involve human injury and death. During the past two decades, on average each year one of 10 moose–vehicle collisions (MVC) caused injuries to passengers in vehicles, including 10–15 human fatalities year^{-1} (SNRA). Various measures to mitigate MVC have been tested in Sweden (Anonymous 1980; Skölving 1985; Björnstig *et al.* 1986) but only exclusion fencing and roadside clearing have proven efficient and become standard in Swedish road management for traffic safety (Lavsund & Sandegren 1991). Results of small-scale experiments have suggested that road fencing may locally reduce the risk for MVC by 80%, while clearing the roadside of cover and forage attractive to ungulates may result in a 20% reduction of accidents (Niklasson & Johansson 1987; cf. Falk, Graves & Bellis 1978; McDonald 1991; Clevenger, Chruszcz & Gunson 2001). By 2001, more than 5000 km of major roads had been fenced against ungulates, with significant extension of mitigation fencing planned (A. Sjölund, SNRA, personal communication).

There are disadvantages to fencing, however. Fencing increases the isolation of wildlife and may become ineffective when animals determined to cross a road force the barrier and eventually get trapped inside the fenced corridor (Nilsson 1987; Seiler *et al.* 2003). Fences that are too short, on the other hand, may not reduce the risk of accidents but simply shift the problem towards the ends of the fences (Ward 1982; Foster & Humphrey 1995; Clevenger, Chruszcz & Gunson 2001). Overall, a better understanding of the factors influencing the spatial distribution of MVC is needed (Malo, Suarez & Diez 2004).

Data on MVC reported to the police were recorded by the SNRA up until 1999. Since 2000, however, these statistics have only included accidents resulting in human injury or death. This implies that more than 95% of all formerly reported collisions now remain unregistered and that identification of road sections with high collision rates is no longer possible using empirical data. Instead, it becomes necessary to model and predict the risk for MVC based on existing knowledge.

Recent studies have shown that collisions between vehicles and animals are aggregated in time and space. Temporal patterns correlate with mating and breeding periods, dispersal of the young-of-the-year, changing food availability, seasonal migrations, temperature, rain fall and snow cover (Jaren *et al.* 1991; Belant 1995; Gundersen, Andreassen & Storaas 1998; Mysterud 2004). Spatial factors include variations in animal abundance, location of preferred foraging habitat, human settlements, landscape topography, road and traffic characteristics and fence location (Bashore, Tzilkowski & Bellis 1985; Child 1998; Finder, Roseberry & Woolf 1999; Hubbard, Danielson & Schmitz 2000; Nielsen, Anderson & Grund 2003). Increased collision risks with animals are associated with linear landscape features that funnel animals alongside or across the road, such as riparian corridors, power lines, steep slopes and ridges and even other transport infrastructures (Bellis & Graves 1971; Feldhamer *et al.* 1986; Clevenger, Chruszczc & Gunson 2003). However, the observed patterns are sometimes ambiguous, non-linear, and dependent on the scale of the investigation and type of road, as well as on the biology of the species (Groot-Bruinderink & Hazebroek 1996; Joyce & Mahoney 2001; Clevenger, Chruszczc & Gunson 2003; Seiler 2004).

Road planners in Sweden and elsewhere (Malo, Suarez & Diez 2004) require simple models to identify road sections where the risk of moose–vehicle collisions is predictably high, and where fences or other permanent mitigation measures would be effective in the long term. The purpose of this study was to develop MVC prediction models based on data that are readily available for road planning at strategic and project levels (Seiler & Eriksson 1997). This study used accident statistics from before 1999, remotely sensed landscape information, digital topographic data and official road and traffic data to identify the strongest set of environmental and road traffic parameters that can be used to foresee the risk of MVC.

Materials and methods

STUDY AREAS

Data comprised the spatial distribution of moose–vehicle collisions (MVC) reported to the police in two regions in south-central Sweden (Fig. 1) with similar habitat conditions, moose populations and road networks. The southern-most region (the model area, 13 569 km^2) included parts of the counties of Östergötland, Jönköping and Kalmar. Logistic regression models were developed that expressed the probability of MVC based on police records for the years 1990–99. These predictions were tested on MVC recorded during the same time period but in the county of Örebro (the test area, 8576 km^2). Both areas are characterized (60% and 65% cover, respectively) by boreo-nemoral conifer-dominated forests containing up to 20% deciduous stands. The forest matrix provides continuous moose habitat, except for lowland areas dominated by agricultural land use. Non-forested land comprised 26% and 17% of the respective study areas, whereas urban areas comprised less than 2% in both areas.

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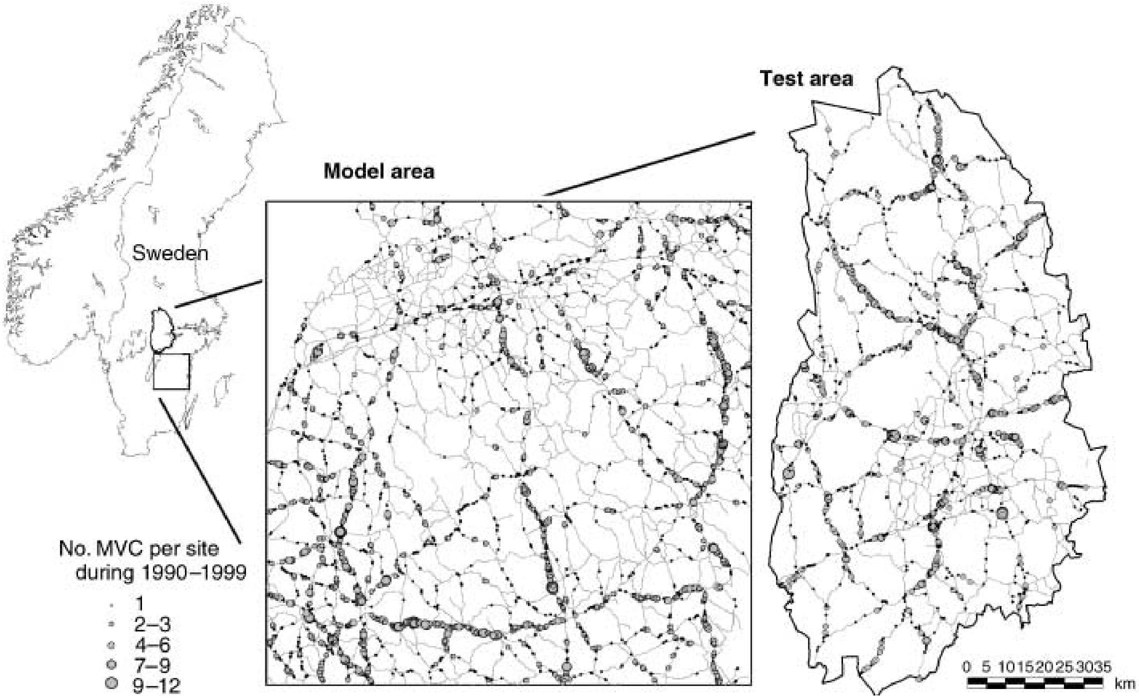

Fig. 1. Distribution of police-reported moose–vehicle collision sites during 1990–99 on the major public road network in the two study areas in south-central Sweden.

Water bodies and wetlands covered the remaining 12–14% of the areas. The landscape relief in the model area was rather flat, rising gradually from sea level in the east to above 360 m in the south-west of the model area, and to 440 m in the north-west of the test area (Sweden Survey 1998). The network of public roads covered about 6600 km in the model area and 3200 kilometres in the test area, resulting in a densities of 0·49 and 0·37 km public road km^{-2} land area, respectively. If private and forest roads were included, road densities approached 1·9 and 1·8 km km^{-2}, respectively.

LANDSCAPE DATA

Land cover data were obtained from Swedish Terrain Type Classification maps (TTC) combined with digital topographic maps at a scale of 1 : 100 000 (Sweden Survey 1998). TTC maps were based on SPOT and Landsat TM thematic satellite images, with a spatial resolution of 25 × 25 metre pixel size, from between 1994 and 1998. These maps were updated with information from aerial photographs and digital thematic maps for wetlands and built-up areas in 1999. Six major land cover types were distinguished from the original 13 TTC land cover classes (Table 1). Classification accuracy in TTC maps varied from 63% for deciduous forest to 92% for coniferous forest and 91% for open land (Anonymous 1991). TTC satellite maps were combined with digital topographic maps to distinguish better agricultural lands from other non-forested areas. In the analyses, arcsine-transformed land cover proportions were used to compensate for skewed distributions (Zar 1998).

Information on linear landscape elements, such as forest edges, water courses, private roads and railways, and point-objects such as houses, bridges and tunnels, were combined from digital road databases and topographic map data. Densities of landscape features were measured as kilometres per square kilometre land, and number of intersections per kilometre road. Distances between the road and landscape elements or habitats were measured in metres and log(e) transformed.

Landscape topography was obtained from the Swedish Terrain Elevation Database with 50 m equidistance (Sweden Survey 1998). Variation in topography was indexed by the density of 10-m altitude isoclines within site buffers.

ROAD AND TRAFFIC DATA

Data on road and traffic characteristics were obtained from digital road databases provided by the SNRA (*status quo* of 1999). Road density averaged 1·92 km km^{-2} in the model area and 1·76 km km^{-2} in the test area. However, 75% of the total road network in both areas was privately owned and not always open to the public. Private roads were mainly local access roads serving forestry or agricultural purposes, usually carrying few vehicles each day. Public roads included international and national trunk roads, motorways and regional and local roads managed by the SNRA or county municipalities. Vehicle traffic was usually concentrated on a few national trunk roads or motorways that carried between 2500 and 20 000 vehicles day^{-1} at speeds mostly above 90 km h^{-1} (66% and 56% of total traffic in the

Table 1. Environmental parameters measured within 500-m radius buffers surrounding moose vehicle collision (MVC) and control sites in the model and the test areas, respectively

Continuous variables	
AGRICULT	Proportion of agricultural land (arcsine)
BUILT-UP	Proportion of urban areas (arcsine)
CONIFER	Proportion of coniferous forest (arcsine)
DECIDUOUS	Proportion of deciduous forest (arcsine)
DIST_FOR	Ln of the distance (m) to nearest forest edge
DIST_X_PRV	Distance (m) to nearest intersection with private road
EDGE_D	Density of land cover type edges (km km^{-2})
FOREST	Proportion of deciduous and coniferous forest (arcsine)
HARVEST	Average annual moose harvest per 100 ha
HOUSE_D	Density of residencies and farms per km^2
LC-DIVERS	Land cover diversity (SIMPSON index)
OPEN	Proportion of open land (arcsine)
PASS_D	Density of road passages across the accident road (per km)
PRIV_RD	Density of private roads (km km^{-2})
PUBL_RD	Density of public roads (km km^{-2})
RAIL_D	Density of railways (km km^{-2})
RELIEF	Variation in topography (density of 10-m isoclines)
RIVER_D	Density of water courses (km km^{-2})
SPEED	Average speed limit on accident road (km h^{-1})
TRAFFIC	Number of vehicles in thousands per average day
WETLAND	Proportion of wetland (arcsine)
XD_FOREST	Density of intersections with forest edges (per km road)
XD_PRIV_RD	Density of intersections with private roads (per km road)
XD_RIVER	Density of intersections with water courses (per km road)
Categorical variable	
FENCE	Occurrence of fences, 'yes' or 'no'

model area and the test area, respectively). Tertiary public roads comprised more than 80% of the public road network but usually carried < 1000 vehicles day^{-1} at signed speeds below 70 km h^{-1} (SNRA database). In 1999, exclusion fences protected between 4% and 3% of the total road network or between 71% and 35% of all primary roads with speed limits above 90 km h^{-1} in the model area and the test area, respectively. In the analyses, the average number of vehicles per day was used jointly with its square to adjust for the humpbacked relationship between traffic volume and MVC frequencies observed in the data (Fig. 2).

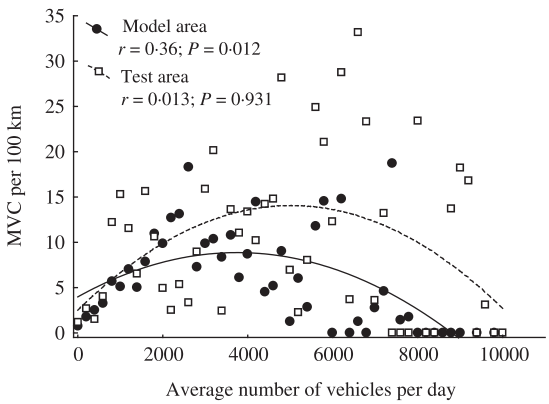

Fig. 2. Relationship between traffic volume (vehicles per average day) and moose–vehicle collisions (MVC) per hundred kilometre road during 1990–99 in both study areas. Traffic volumes at accident sites are grouped into 51 classes of 200 vehicles day^{-1}. MVC densities are averaged over corresponding traffic classes. The data are based on 2000 and 1300 MVC sites in the model and the test area, respectively.

MOOSE–VEHICLE COLLISIONS

Data on moose–vehicle collisions were obtained from the SNRA road accident statistics containing all police-reported accidents on public roads between 1972 and 1999. Each database record contained information on the type of accident, place and time. The accuracy of this information was not evaluated, but police and hunters independently estimated an average error of ± 500 m in the localization of the accidents (L. Sävberger, personal communication). Accident records for the model area and test area from 1990 to 1999 amounted to 2185 and 1655, respectively, averaging 216 ± 16·6 (± SD) and 166 ± 26·2 MVC $year^{-1}$ and $area^{-1}$, respectively, with no general trend in the annual numbers. The frequencies of 0·06 MVC and 0·078 MVC million kilometres $driven^{-1}$ in the respective areas were close to the national average of 0·068 MVC million kilometres $driven^{-1}$ in Sweden (SNRA database).

MOOSE ABUNDANCE AND HARVEST

Throughout both the model and test areas, moose were abundant and common. Moose densities are generally higher in forested landscapes, but individual moose range even in highly urbanized areas (A. Seiler, personal observations). Indices of moose abundances were determined from the average annual game bag per hunting district during the 1990s. In the model area (21 hunting districts) and test area (14 districts), county administrative board records revealed similar, slightly decreasing trends in moose harvest since 1990. On average, about 3·45 moose were shot per thousand hectares in the model area, and 4·25 in the test area, during 1993–97. Among individual hunting districts, the average moose harvest varied from 1·0 to 5·1 1000 ha^{-1} in the model area and from 1·6 to 6·4 in the test area. Although game bag statistics are generally subordinate to hunter observations or pellet counts in reflecting trends and patterns in ungulate populations (Ericsson & Wallin 1999; Solberg & Saether 1999), only harvest data covered a sufficiently large area and time period for the analysis. Moose harvest and MVC were shown to correlate strongly at county and national levels over the past 30 years (Seiler 2004).

Moose populations in the two study areas did not migrate between distant winter and summer ranges, as is common for their conspecifics north of about 60°N (Sweanor & Sandegren 1989; Ball, Nordengren & Wallin 2001). It is possible that in northern regions seasonal migration produces a pattern in MVC that deviates from the one studied here (Lavsund & Sandegren 1991). Hence the results of this study may only partly apply to north Swedish conditions.

STATISTICAL ANALYSES

Model composition

Multiple logistic regression analyses (Hosmer & Lemeshow 1989) were used to identify parameters that significantly distinguished between observed MVC sites and non-accident control sites. After excluding incomplete MVC records, a subset of 2000 MVC was selected from 2185 records for further analysis, and an equal number of randomly distributed non-accident control sites that were located at least 1 km away from any reported accident site was created. At each accident and control site, a 500-m radius buffer was developed to account for the presumed error of ± 500 m in the reported location of MVC (see above). Within these buffers, 25 different road traffic and landscape parameters were assumed to influence the risk of MVC (Table 1). Site status (MVC or control) constituted the binary response variable used in the logistic regression analyses.

Unpaired *t*-tests and univariate logistic regression models were used to identify variables that significantly ($P < 0·1$) differed between accident sites and control sites. In all other analyses, significance levels were set at $P < 0·05$. To reduce intercorrelation between the selected variables (Zar 1998), agriculture and conifer were omitted from further analyses as they were highly correlated ($R > 0·75$) with the edge density but less effective in distinguishing between control and MVC sites.

The remaining 19 variables were grouped into three a priori models representing parameter combinations useful in different phases in road management. The simplest model (road–traffic model) included only basic road and traffic parameters that are readily available in strategic environmental impact assessment (SEA) or strategic road management. The second model (landscape model) contained only parameters obtained from remotely sensed landscape data and digital maps providing information on the background MVC risk in an unexploited area. This model could also be used in SEA. Once the routing of a new road is decided, or if the road in question already exists, data on road, traffic and environment can be combined with additional information on the juxtaposition of landscape elements relative to the road. A combined model thus provides a tool for the evaluation of alternative routes in environmental impact assessment (EIA) at the project level or for the identification of road sections with high risks of MVC.

For the construction of the multiple models, stepwise (backward) regression procedures were used to identify significant parameter combinations. The different variable sets were compared using Akaike's information criteria (AIC) and Akaike weights (w_i) to identify the most parsimonious model (Burnham & Anderson 2002). Model structure was considered adequate if variance inflation factors (ratio of goodness-of-fit χ^2 statistic to its degrees of freedom) were close to 1·0 (Cox & Snell 1989, cited in Burnham & Anderson 2002). The observed inflation factors ranged between 1·003 and 1·006, suggesting that variable width was scaled appropriately and that the data was not overdispersed. Calculations were performed with the statistical software packages STATISTICA (StatSoft 1999) and StatView (SAS Institute Inc. 1998).

Model validation

The predictive abilities of the subsets for the three a priori models were tested in the county of Örebro on regularly distributed 1-km road sections classified as either accident sites (if at least one MVC occurred during the period of 10 years) or non-accident sites (if the distance to the nearest MVC location exceeded 1 km). A random sample of 1300 accident sites was selected from a total of 1573 road sections with MVC, together with an equal number of non-accident sites, to obtain a balanced sample. Environmental parameters were quantified within a 500-m radius around the centre-point of each accident or control road section. To determine how the different models performed in distinguishing between accident and non-accident sites in the test area, nivariate logistic regression analyses were used with the actual status of the test sites as a binary response variable and the site-specific probability for MVC as an independent predictor.

Counteractive measures

To illustrate and evaluate the predicted effect of different counteractive measures on accident risks, changes in MVC probabilities relative to varying traffic volume and moose abundance (harvest statistics) were modelled with respect to increased forest proximity (+ 100 m), reduced vehicle speed and road fencing. Modelling was done using the logistic regression functions of the best models, gradually changing the selected predictor variable(s) while keeping all other variables included in the corresponding model at their observed means.

Results

TRAFFIC AND MVC DENSITIES

The distribution of MVC along public roads was non-random in both the model area and test area. MVC were more common on roads with intermediate to high traffic volumes (Fig. 2). A maximum of 10·7 and 16·7 MVC hundred kilometres^{-1} and year^{-1} were recorded on roads with traffic volumes between 2000 and 4000 adt (average daily number of vehicles) in the model area and 4000–6000 adt in the test area, respectively. Roads with even higher traffic volumes did not produce significantly higher MVC rates. Because of this unimodal pattern, fitting traffic volume and its square jointly in a multiple regression model achieved significance (model area: adjusted $R^2 = 0{\cdot}32$, $F_{2,45} = 11{\cdot}959$, $P < 0{\cdot}0001$; test area: adjusted $R^2 = 0{\cdot}13$, $F_{2,47} = 4{\cdot}747$, $P < 0{\cdot}013$; Fig. 2).

MVC were also more common on roads with intermediate to high speed limits (model area: $\chi^2 = 12{\cdot}70$, d.f. = 3, $P < 0{\cdot}0053$; test area: $\chi^2 = 17{\cdot}83$, d.f. = 3, $P < 0{\cdot}0005$; Fig. 3a). Maximum MVC densities were associated with speed limits of 90 km h^{-1}, whereas lower or higher speed limits on unfenced roads produced fewer accidents with moose. About 57% of all MVC were recorded on roads with speed limits of 90 km h^{-1}, and more than 20% of these MVC involved human injuries or death. Of all MVC resulting in human injury or death, about 65% ($n = 143$) and 83% ($n = 139$) occurred on 90 km h^{-1} roads in the model area and test area, respectively (Fig. 3b). MVC densities were increased in areas that supported high moose harvests (model area: $r^2 = 0{\cdot}37$, $F_{1,19} = 12{\cdot}790$, $P < 0{\cdot}002$; test area: $r^2 = 0{\cdot}19$, $F_{1,12} = 2{\cdot}822$, $P < 0{\cdot}119$; Fig. 4.

MODEL RESULTS

Unpaired *t*-tests and univariate logistic regression analyses revealed significant differences in most environmental variables between MVC sites and non-accident control sites in the model area (Table 2). MVC sites were characterized by higher traffic volumes, increased speed limits and a higher proportion of mitigation fences compared with control sites. The probability of MVC increased with the density of private roads, the amount of coniferous and deciduous forest cover in the vicinity of the road, and the proximity to the nearest forest edge. Collision probabilities decreased with the proportion of urban habitats and agricultural land, and with the density of public roads, railways and watercourses. Control sites and MVC sites were similar relative to the density of water crossings, density of settlements and topographical variation.

The three a priori models were highly different in their ability to predict the observed likelihood for MVC (Table 3). The traffic model ranked highest according to AIC weights ($w_i = 95\%$). Despite the small number of variables included, it classified correctly 81·2% of the observations. The predictions made by the combined model classified correctly 83·6% of all observations but,

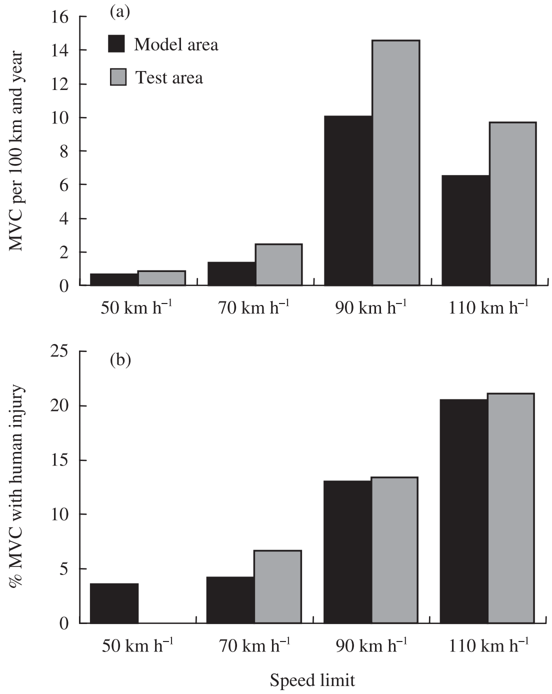

Fig. 3. Numbers of moose–vehicle collisions (MVC) per hundred kilometres and year during 1990–99 for different road categories in the model area ($n = 2185$ MVC) and test area ($n = 1655$ MVC). (a) MVC densities on roads with different speed limits. (b) Percentage of MVC that involved human injury or death depending on the speed limit of the accident road.

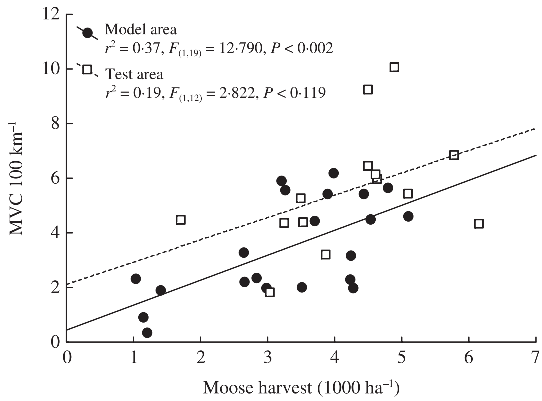

Fig. 4. Relationship between the average annual density of moose–vehicle collisions (MVC) per hundred kilometres road and the average number of moose shot 1000 ha^{-1} in hunting districts (model area, $n = 21$; test area, $n = 14$) during the years 1990–99 in the two study areas.

Table 2. Descriptive statistics and univariate comparison of environmental variables in the model area measured within a 500-m radius surrounding 2000 moose vehicle collision (MVC) sites and 2000 control sites randomly placed along public roads at distances of more than 1 km from the nearest collision site. Definitions of the variables in Table 1

	MVC sites			Control sites			Unpaired *t*-test	
Variable	Mean	SD	Maximum	Mean	SD	Maximum	*t*-value	*P* -value
SPEED	85·10	12·78	110·0	68·84	13·99	110·0	−38·36	< 0·0001
TRAFFIC	2·117	1·774	9·790	0·651	1·420	9·622	−38·01	< 0·0001
EDGE_D	0·041	0·012	0·069	0·034	0·015	0·069	−14·53	< 0·0001
PRIV_RD	1·429	0·865	4·546	1·100	0·740	4·511	−12·93	< 0·0001
FOREST	53·86	17·83	86·88	45·42	23·74	88·49	−12·71	< 0·0001
HARVEST	3·205	1·045	5·100	2·740	1·162	5·100	−12·69	< 0·0001
DECIDUOUS	22·96	9·82	50·21	18·72	11·64	54·53	−12·47	< 0·0001
DIST_FOR	49·83	98·03	1371·0	99·43	186·0	1637	10·55	< 0·0001
AGRICULT	24·04	16·34	90·00	29·56	21·80	88·66	9·07	< 0·0001
DIST_X_PRV	174·6	147·6	0·03	225·8	231·6	0·04	8·34	< 0·0001
CONIFER	30·90	15·80	80·49	26·71	17·99	88·31	−7·83	< 0·0001
LC-DIVERS	3·124	1·152	21·2	2·847	1·335	22·11	−7·04	< 0·0001
OPEN	30·55	7·52	69·95	28·74	9·29	87·67	−6·75	< 0·0001
PUBL_RD	1·332	0·311	7·180	1·390	0·314	4·593	5·85	< 0·0001
XD_PRIV_RD	4·498	3·073	0·00	3·903	3·819	0·00	−5·43	< 0·0001
BUILT-UP	2·024	6·662	54·80	3·328	10·68	65·31	4·63	< 0·0001
RAIL_D	0·163	0·404	1·614	1·334	12·10	197·7	4·32	< 0·0001
WETLAND	5·049	6·590	44·40	4·381	5·977	47·31	−3·35	0·0008
PASS_D	0·070	0·331	3·991	0·102	0·404	7·433	2·76	0·0058
XD_FOREST	1·832	1·542	7·024	1·972	1·871	13·1	2·56	0·0106
RELIEF	0·012	0·005	0·035	0·012	0·006	0·040	1·78	0·0747
HOUSE_D	5·221	4·721	33·27	5·099	5·275	33·27	−0·78	0·4383
RIVER_D	0·405	0·576	2·646	0·414	0·570	2·588	0·50	0·6149
XD_RIVER	0·209	0·404	1·540	0·203	0·404	4·019	−0·50	0·6177
Categorical variable	%	MVC	Controls	d.f.	χ^2	*P*-value		
FENCE	Yes	5·6	1·8	1	43·33	< 0·0001		

because of the increased number of included variables, its relative AIC weight was only 5%. The landscape model performed less well, yet it predicted correctly 67·5% of the actual MVC sites and 62·2% of the control sites.

VALIDATION RESULTS

Simple logistic regression analyses, using the predicted likelihoods for MVC as the independent variable and the actual accident status of the selected road sections in the test area as the dependent variable, gave strong support for the combined model (Table 4). This model obtained 100% of the relative AIC weights compared with the two other models and predicted 72·4% of all actual MVC sites and 79·8% of all control sites correctly. These concordances were similar to those obtained in the model area. However, the traffic model and landscape model were also significant, producing overall concordances of 77·9% and 62·0%, respectively. Thus, all three models succeeded in distinguishing between non-accident and accident road sections in the test area.

EFFECT OF COUNTERACTIVE MEASURES

Based on the combined model, speed reduction appeared to be the most effective measure to reduce MVC risk at any given traffic volume. However, the effect was modified by fencing, moose abundance and forest proximity (Fig. 5a,b). On unfenced roads with adjacent forest cover and traffic volumes of 5000 vehicles day^{-1} in areas producing an annual harvest of 3 moose 1000 ha^{-1}, a reduction in the speed limit from 90 km h^{-1} to 70 km h^{-1} would reduce the risk for MVC by only 5%. A better result could be achieved by increasing the distance to adjacent forest by, for example, 100 m (3% reduction) or by fencing (9% reduction). Fencing of a 90-km h^{-1} road in combination with increased road clearance (100 m) could, however, lower collision risk by 26%. If speed is lowered to 70 km h^{-1}, collision risks could be reduced by 65%. Fencing appears to be most effective, although not cost-effective, on minor roads with limited vehicle speed. According to the traffic model, the effect of fencing is greater on roads with low and high traffic volumes, because of the unimodal relationship between traffic volume and MVC densities (Fig. 5b).

Discussion

The spatial distribution of moose–vehicle collisions was not random. Collisions were a product of various environmental factors, which could be quantified from remotely sensed landscape information, road traffic data and estimates of animal abundance. In this respect, these results concurred with other studies on animal–vehicle collisions (Bashore, Tzilkowski & Bellis 1985; Finder, Roseberry & Woolf 1999; Hubbard, Danielson

Table 3. Results of three logistic regression models describing the influence of road traffic and environmental factors on the probability of moose–vehicle collisions (MVC) per kilometre public road in the model area during 1990–99

	Coefficient	SE	χ^2	Part. *R*	*P*		
Traffic model							
Constant	−7·580	0·351	466·72	−0·293	< 0·0001	Model *P*	< 0·0001
SPEED	0·088	0·005	323·37	0·243	< 0·0001	Rho^2	0·341
TRAFFIC	1·417	0·080	316·43	0·241	< 0·0001	AIC	2838·5
TRAFFIC(SQ)	−0·194	0·012	243·67	−0·211	< 0·0001	ΔAIC	0
FENCE	−0·947	0·280	11·481	−0·042	0·0007	w_i	0·95
						Concordance	
						Control	89·7%
						MVC	72·7%
						Total	81·2%
Combined model							
Constant	−9·88	0·594	276·92	−0·236	< 0·0001	*P*-value	< 0·0001
TRAFFIC	1·553	0·090	297·96	0·245	< 0·0001	Rho^2	0·424
SPEED	0·081	0·005	222·53	0·212	< 0·0001	AIC	2861·3
TRAFFIC(SQ)	−0·177	0·013	185·89	−0·193	< 0·0001	ΔAIC	22·8
FENCE	−2·050	0·302	46·10	−0·095	< 0·0001	w_i	0·05
RELIEF	−59·97	8·930	45·10	−0·094	< 0·0001	Concordance	
HARVEST	0·038	0·006	42·47	0·091	< 0·0001	Control	89·2%
DECIDUOUS	0·310	0·049	39·61	0·087	< 0·0001	MVC	78·0%
XD_FOREST	−0·235	0·038	38·71	−0·086	< 0·0001	Total	83·6%
XD_PRIV_RD	0·091	0·017	30·27	0·076	< 0·0001		
EDGE_D	32·61	6·505	25·13	0·069	< 0·0001		
OPEN	0·028	0·006	19·77	0·060	< 0·0001		
DIST_FOR	−0·256	0·066	14·95	−0·051	0·0001		
FOR*DIST_FOR	0·004	0·001	9·322	0·039	0·0023		
Landscape model							
Constant	−2·73	0·191	204·34	−0·201	< 0·0001	*P*-value	< 0·0001
RELIEF	−68·98	6·980	97·66	−0·138	< 0·0001	Rho^2	0·105
PRIV_RD	0·406	0·046	77·64	0·123	< 0·0001	AIC	4755·7
DECIDUOUS	0·028	0·004	55·43	0·103	< 0·0001	ΔAIC	1917·3
EDGE_D	23·34	3·305	49·87	0·098	< 0·0001	w_i	0·00
OPEN	0·031	0·005	45·35	0·093	< 0·0001	Concordance	
HARVEST	0·237	0·037	40·78	0·088	< 0·0001	Control	62·2%
RAIL_D	−0·030	0·013	5·634	−0·027	0·0176	MVC	67·5%
BUILT-UP	−0·010	0·004	5·447	−0·026	0·0196	Total	64·8%

& Schmitz 2000; Clevenger, Chruszczc & Gunson 2003; Nielsen, Anderson & Grund 2003; Malo, Suarez & Diez 2004). Overall, moose–vehicle collisions were most likely to occur on unfenced roads with intermediate traffic volumes and intermediate speed limits, and in hunting districts that produced large moose harvests.

The high predictive power of the traffic model was surprising. With knowledge of traffic volume, speed limitation and the occurrence of exclusion fences, about 73% of the actual MVC sites in both the model and the test area could be foreseen, provided that moose were abundant and widespread across the landscape. This lends strong support to a categorical distinction between low-risk and high-risk roads that may serve sufficiently well to guide road planners in the strategic evaluation of mitigation needs against MVC. Within a given road category, however, additional environmental information is needed to differentiate between low-risk and high-risk road segments. By combining road traffic with landscape parameters, the combined model helps locate and compare MVC risks among different routing alternatives and mitigation options. More

Table 4. Results of the univariate logistic regression models testing the predictions of three models on 1300 randomly selected road sections with moose–vehicle collisions (MVC) reported during 1990 and 1999, and equal numbers of non-accident control sections

	Model		
	Combined	Traffic	Landscape
Validation results			
Coefficient	4·21	4·40	3·27
SE	0·16	0·18	0·22
χ^2	656·7	573·8	220·1
d.f.	1	1	1
McFadden's rho^2	0·253	0·215	0·068
P-value	< 0·0001	< 0·0001	< 0·0001
Log likelihood	−1347·1	−1414·2	−1679·0
AIC	2698·2	2832·5	3362·0
ΔAIC	6·04	0	11
w_i (%)	4·6	0·0	0·4
Concordance with actual status (%)			
Control	79·8	83·6	59·4
MVC	72·4	72·1	64·6
Total	76·1	77·9	62·0

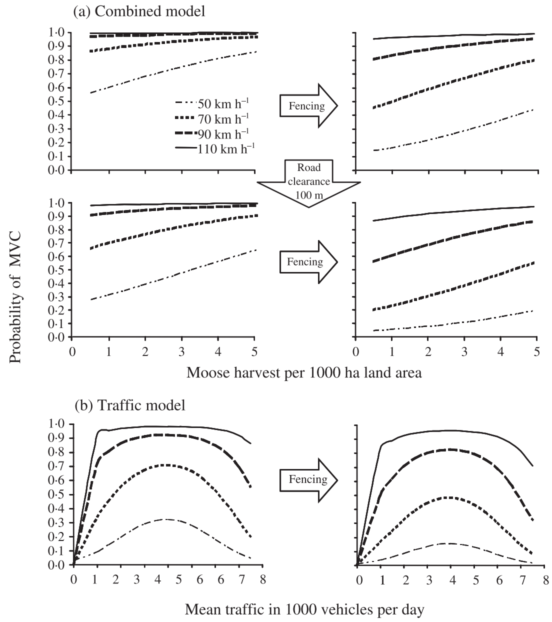

Fig. 5. Visualization of the combined effects of vehicle speed, traffic volume, fencing, moose abundance (game bag statistics) and proximity of forest on the likelihood of at least one MVC occurring km^{-1} over a 10-year period. (a) Predictions of the combined model for roads with a traffic volume of 5000 vehicles average day^{-1} and with all other variables included in the model kept constant at the observed means (see Tables 2 and 3). (b) Predictions of the traffic model with intercepts forced through the origin.

detailed knowledge of the local abundance and mobility of moose (Etter *et al*. 2002), occurrence of preferred moose forage (Ball & Dahlgren 2002; Seiler *et al*. 2003), embankment of the road (Clevenger, Chruszczc & Gunson 2003) and driver visibility (Bashore, Tzilkowski & Bellis 1985) would increase the predictive power of such models in a given area.

Without information about the road, its traffic or the location of the road relative to other landscape features, predicting MVC is possible but with a 35% risk of failure, which, in the case of road accidents, can be significant. Never the less, at a strategic planning level (cf. Seiler & Eriksson 1997), the landscape model may provide a useful first guidance for the gross identification of high-risk areas.

Caution is needed, however, if the models are to be applied to regions that differ substantially from the study areas with respect to landscape composition and moose behaviour. In regions dominated by agriculture, where moose habitat is restricted, and in northern latitudes, where moose are partially migratory (Ball, Nordengren & Wallin 2001), the actual pattern in MVC are likely to deviate from that reported here.

FACTORS INFLUENCING MVC RISKS

Traffic parameters

Traffic volume and vehicle speed were important predictors of collision risks with moose. However, the effects were not linear but peaked at intermediate speed limits and intermediate traffic volumes. Similar patterns have been reported by others (Berthoud 1987; Skölving 1987; Clarke, White & Harris 1998; Seiler 2004), suggesting that intensive traffic may repel wildlife from approaching roads and thereby reduce the likelihood of accidents. Müller & Berthoud (1997) recommended considering roads with traffic volumes between 1000 and 10 000 vehicles average day^{-1} as significant sources of mortality, but as insurmountable barriers if traffic volumes exceeded 10 000 vehicles day^{-1}. The unimodal effect of traffic volume on collision risk is a local phenomenon involving the behaviour of individual animals and therefore is not comparable with the broad-scale linear correlation between traffic intensity and collision numbers commonly observed (McCaffery 1973; Oosenbrug, Mercer & Ferguson 1991; Seiler 2004).

Moose abundance

The relationship between deer density, as indexed by hunting statistics, and the frequency of collisions with vehicles has often, but not always, been found to be strongly positive (McCaffery 1973; Groot-Bruinderink & Hazebroek 1996; Child 1998). Also in this study, MVC sites were associated with significantly higher moose harvests than control sites, in contrast with Almkvist *et al*. (1980) and Seiler (2004). These authors did not find a correlation between local moose harvest and the frequency of MVC and questioned the value of harvest statistics in indexing local variations in moose density. Management for reduced moose densities along roads may not necessarily result in reduced collision risks or be politically or economically feasible (but cf. Putman 1997; Schwabe, Schuhmann & Tonkovich 2002). Individual animals may be more mobile in areas with high hunting pressure than in more densely populated areas (Henderson *et al*. 2000). Increased mobility increases the likelihood that inexperienced moose will encounter traffic and roads. MVC in Sweden tend to increase during the first 2–3 years following construction of a new road (A. Seiler, unpublished data), a pattern that suggests a perturbation and consequent adaptation in the spatial arrangement of moose home ranges or the killing of individuals whose home ranges brought them into direct contact with the road (Reilly & Green 1974; Jones 2000). In their survey of mitigation measures applied across the USA, Romin & Bissonette 1996) reported success in only one of two states that tried to reduce deer–vehicle collisions through intensified hunting. Joyce & Mahoney (2001) documented that the risk for MVC along the Trans-Canada Highway in Newfoundland was elevated in areas with both scarce and dense moose populations, but was reduced in intermediate areas.

Landscape features

Moose movement and activity can be affected by altering landscape composition in the vicinity of roads. For example, young pine plantations and clear-cuts with a high proportion of deciduous vegetation provide important staple forage for moose in Sweden (Bergström & Hjeljord 1987; Cederlund & Okarma 1988). Thus, MVC are more frequent on roads traversing clear-cuts and young forests compared with similar roads in agricultural areas (Almkvist *et al*. 1980). Based on the model reported here, the amount and proximity of forest habitat that provides cover and forage significantly affects the risk of MVC. An increase of 100 m in the distance between forest cover and the road may reduce the risk of collisions with moose by 15%. However, if vehicle speed and moose density were increased simultaneously, the effect of forest proximity would be weaker. Forest cover and its proximity to the road are also important predictors of collision risks with other ungulates, such as white-tailed deer *Odocoileus virginianus* Zimm in Illinois and Pennsylvania (Puglisi, Lindzey & Bellis 1974; Bashore, Tzilkowski & Bellis 1985; Finder, Roseberry & Woolf 1999) and roe deer in Austria and France (Kofler & Schulz 1987; Berthoud 1987). Yet the effect of forest habitat depends on the composition of the wider landscape; where preferred habitat is extensive and common, deer accident sites were more randomly distributed (Allen & McCullough 1976; Bashore, Tzilkowski & Bell 1985; Feldhamer *et al*. 1986).

Road passages

Numerous reports suggest that linear landscape elements such as riparian corridors, ditches, steep slopes and ridges, as well as fences and other transport infrastructure, may funnel animals alongside or across the roadway and thereby increase the risk of deer–vehicle collisions (Madsen, Fyhn & Prang 1998; Finder, Roseberry & Woolf 1999; Hubbard, Danielson & Schmitz 2000; Malo, Suarez & Diez 2004). There is evidence that the risk of deer accidents increases where exclusion fences terminate or are interrupted by interchanges and connecting minor roads (Ward 1982; Foster & Humphrey 1995; Clevenger, Chruszczc & Gunson 2001). In this study, the risk of MVC was elevated where private roads connected to the main (accident) road, irrespective of whether the road was fenced or not, but the risk decreased where tunnels or bridges separated the intersecting roads. Similarly, the density of road passages had a significant effect on the density of collisions with moose and roe deer per parish (Seiler 2004). This suggests that conventional bridges and tunnels may, to a limited degree, provide passage to wildlife and thereby reduce the likelihood of animals crossing roads (Yanes, Velasco & Suarez 1995; Rodriguez, Crema & Delibes 1996; Clevenger & Waltho 2000). Likewise, Hubbard, Danielson & Schmitz (2000) observed that bridge density increased the likelihood of accidents with white-tailed deer in Iowa and suggested that bridges near travel corridors were not accepted by the animals. The exact location and design of wildlife underpasses is crucial in determining the efficacy of these measures in reducing wildlife mortality (Lodé 2000; Keller & Bekker 2003).

MITIGATION MEASURES

The risk of moose–vehicle collisions in Sweden can be predicted to a high degree from remotely sensed landscape data in combination with official road traffic data. Although moose vehicle collisions occurred on nearly all roads within the study areas, the risk varied with traffic volume, amount and proximity of forest, road intersections and moose density. Many of the landscape/habitat parameters associated with the risk of collisions are the responsibility of landowners and beyond the influence of the road administration. Mitigation options are mainly limited to the road and its immediate surrounding. According to the models, reduced vehicle speed in combination with fencing and increased roadside clearance provides the strongest mitigation against MVC available to the SNRA. Adaptation of underpasses and bridges to wildlife needs may further improve traffic safety. The significance of vehicle speed in all models further suggests that the drivers' reaction plays an important role in accidents. However, educational programmes to enhance public awareness about wildlife–vehicle relationships have not yet proven effective (Romin & Bissonette 1996). The spatio-temporal correlation of collisions (Almkvist, André & Ekblom 1980; Gundersen, Andreassen & Storaas 1998) must be studied in order to develop more cost-efficient mitigation measures for implementation during high risk times and at high risk sites only. The models presented here may provide useful tools for road planners, but effective mitigation against MVC will require a more holistic approach that includes integrated management of the surrounding landscape and the moose population, as well as increased awareness by individual drivers.

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Received 8 January 2004; final copy received 20 December 2004