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GIS-BASED MODELING APPROACHES TO IDENTIFY MITIGATION PLACEMENT ALONG ROADS

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Abstract: Decision-making in the design of effective wildlife passage structures is hampered by the sparse information currently available. There are several reasons for this deficiency. Monitoring wildlife passages is not often anticipated after construction. There are few methodological approaches to identify the placement of wildlife passages. Finally, there is an urgent need for mitigation procedures that contemplate the broad landscape context of road systems. When used in a geographic information system (GIS) environment, regional or landscape level connectivity models of sufficient resolution can help delineate placement of wildlife crossing structures. GIS tools and applications are becoming more popular among resource managers and transportation planners. An empirically based habitat linkage model is preferred to qualitative or conceptual models based on limited data. However, in many cases, the data necessary for empirically based models are not available. As a substitute, expert information can be used to develop simple, predictive, habitat linkage models in a relatively short period of time. Banff National Park is preparing for a new Trans-Canada highway (TCH) expansion and mitigation project. We need to be able to provide park managers with an empirical assessment of the impediments posed by transportation corridors to animal movements, and recommend the placement of mitigation measures. For some species there are empirical data, while for others there are little or no data. Given this situation, we developed several GIS approaches to model animal movements across transportation corridors in the Central Rocky Mountains. For a single species, we developed three different but spatially explicit habitat models to identify linkage areas across the TCH. One model was based on empirical data, and the other two models were based on expert opinion and expert literature. We used the empirical model as a yardstick to measure the accuracy of the expert-based models. Our tests showed the expert literature-based model most closely approximated the empirical model, both in the results of statistical tests and the description of the linkages. For a similar exercise using empirical data, we developed a multi-scale GIS approach to model multiple species movements across the TCH and identify mitigation passage placement. Three steps were involved: 1) the creation of regional habitat suitability models for each of four large mammal species, 2) the development of a regional scale movement component to the models, and (3) nested within step 2, the construction of local-scale movement models of high spatial resolution within the transportation corridor. Recommendations regarding the location of potential mitigation based on the intersection of simulated pathways with transportation corridors and other human infrastructure were the result of the exercise. Our empirical and expert models represent useful tools for resource and transportation planners charged with determining the location of mitigation passages. Expert models were shown to be practical when baseline information is lacking and time constraints do not allow for pre-construction data collection. It is important to note the wide applicability of such models to other planning issues in the Central Rocky Mountains. The proposed models could be applied to other human infrastructure, such as railways, trails, or other road systems.

Introduction

Wildlife crossing structures have been designed and incorporated into road construction projects to mitigate the effects of road barriers (Foster and Humphrey 1995, Keller and Pfister 1997, McGuire and Morrall 2000). Although effective crossing structure designs have been formulated for single species and multispecies assemblages (Singer and Doherty 1985, Rodríguez et al. 1996, Clevenger and Waltho 2000), few methodological approaches to determine the placement of highway mitigation passages have been explored. Traditional road planning and mitigation designs have been site-specific and one-dimensional, i.e. linear, thus failing to incorporate the broad landscape context of road systems (Forman 1987). When used in a geographic information system (GIS) environment, regional or landscape level connectivity models of sufficient resolution can help identify potential highway crossing or linkage areas for wildlife (Servheen and Sandstrom 1993, Singleton and Lehmkuhl 1999, Clevenger et al. in press).

Within the Canadian Rocky Mountains, habitat fragmentation and physical barriers undermine the integrity of the vast ecological network. Major transportation corridors and road networks are of greatest concern and perhaps the greatest obstruction to conserving large animal populations in the entire area (Noss et al. 1996). As part of a project aimed at evaluating, designing and planning highway mitigation measures along the Trans-

Canada highway (TCH) in Banff National Park (BNP), Alberta, we have developed GIS-based approaches to modeling animal movements across transportation corridors in the Central Rocky Mountains.

Banff National Park is preparing for a new Trans-Canada highway (TCH) expansion and mitigation project. We need to be able to provide park managers with an empirical assessment of the impediments posed by transportation corridors to animal movements and recommend the placement of mitigation measures. For some species there are empirical data, while for others there are little or no data. Thus, several GIS approaches were developed to model animal movements across transportation corridors in the Central Rocky Mountains.

For a single species, we developed three different but spatially explicit habitat models to identify linkage areas across the TCH. One model was based on empirical data, while the other two were based on expert opinion and expert literature. We used the empirical model as a yardstick to measure the accuracy of the two expert-based models (Clevenger et al. in press).

For a similar exercise using empirical data, we developed a multi-scale GIS approach to model multiple species movements across the TCH and identify mitigation passage placement. Three steps were involved: 1) the creation of high-resolution, regional habitat suitability models for each of four species, 2) the development of a regional scale movement component to the models, and (3) nested within step 2, the construction of local-scale movement models of high spatial resolution within the transportation corridor. Recommendations regarding the location of potential mitigation based on the intersection of simulated pathways with transportation corridors and other human infrastructure were the result of the exercise.

Study Area

Our extensive study area encompassed Banff, Kootenay and Yoho National Parks located in the Central Canadian Rocky Mountains, Canada. Specifically, we focused on the Trans-Canada highway (TCH) transportation corridor in Banff National Park (BNP), Alberta (Fig. 1). There are probably few places in the world where the intersection of transportation corridors with wildlife corridors is as significant as in the Canadian Rocky Mountain national parks. Banff and Yoho are the only national parks in North America to have a major transportation corridor running through them. Situated approximately 120km west of Calgary, Banff is the most heavily visited national park in North America with over 5 million visitors per year. The highway also is a major commercial motorway between Calgary and Vancouver. In 1998, annual daily traffic volume at the park east entrance was 14600 vehicles per day and summer annual traffic volume was 21500 vehicles per day (Parks Canada Highway Service Centre, unpublished data).

Fig. 1. The location of the Trans-Canada highway study area in relation to the entry-exit points (numbered 1 to 11) used in simulating regional scale, large mammal movements in the Central Canadian Rocky Mountains, Canada.

Major transportation corridors can seriously alter ecosystem processes. Mitigating the effect of the TCH on the park environment is an obvious necessity. Since the 1980s, fencing and 24 wildlife crossing structures (overpasses and underpasses) have been installed along the first 45 km of TCH in BNP (McGuire and Morrall 2000). The remaining 30km to the British Columbia border is currently two lanes and unfenced; however, four-lane expansion with appropriate mitigation measures for wildlife is imminent.

The Trans-Canada highway in BNP runs along the floor of the Bow Valley, sharing the valley bottom with the Bow River, the township of Banff (population 9000), several high volume two-lane highways, numerous secondary roads, and the Canadian Pacific Railway. The geography of central and eastern BNP is dictated by the geology of the Front Ranges of the Rocky Mountains. This geography influences the distribution and movement of wildlife in the park. The parallel NNW-SSE oriented limestone ridges and shale valleys create a landscape much more conducive to the North-South than the East–West movement. The few large valleys, the Bow Valley being the most prominent of them, that dissect the Front and Central Ranges are recognized as critical not only in maintaining the regional-scale East-West movements, but also in providing a vital link between the valleys nested among the Front Ranges of the park. For these same reasons, the Bow Valley is also one of the most important of the transportation corridors in the region.

Methods

Expert-Based Linkage Models

Empirical model

We selected black bears (*Ursus americanus*) to model habitat use and identify linkage areas across the TCH. Black bears were the only species for which we had sufficient empirical data to build a habitat model and enough data from crossings and mortality locations to test the model. Furthermore, we assumed that mortality locations were crossing locations although we were unable to prove that the unsuccessful crossing locations were different from successful ones.

To develop the empirical habitat model, we first determined the habitat characteristics of black bears in the study area using nine biophysical variables in the analysis. Location data were obtained from monitoring the movements of nine radio-collared bears between 1998-99. We used a probability function that ties the distribution of bear locations to the variables in the study area (Pereira and Itami 1991, Manly et al. 1993). To incorporate black bear landscape perception depth, we tied the dimensions of the kernels (= 500m radius) used to calculate landscape indices and radiotelemetry density maps with the reported black bear average daily movement rates (Garshelis et al. 1983, Alt et al. 1980). To account for the telemetry error, each location was buffered 175 meters (the maximum average error) and assigned a probability of occurrence (PO) value. To facilitate statistical analysis, we stratified the density maps into PO classes. We removed all density values less than 0.5 animals per kernel area (the null class), and calculated the 25th, 50th and 75th percentile for each of the density distributions. These percentiles were used as the cut-out values in defining four PO categories: low (<25%), moderate (25-50%), high (50-75%), and very high (>75%). A stratified random sample of points (n = 580) was generated to compare with the landscape and biophysical variables in each of the PO categories.

Our sample of marked animals was not random or large enough to represent the black bear population. Therefore we decided against the univariate selection vs. avoidance method of habitat modeling. Instead we identified directional trends in habitat selection across the full set of PO categories, supported by a statistical analysis of the observed patterns. This approach overcomes problems associated with small sample sizes and potential spatial autocorrelation of the study animals; however, it does not fully mitigate the effects of their non-random selection.

We used a multivariate discriminant function analysis (DFA) to assess the relative importance of the biophysical variables to bear habitat selection. We used the Mahalanobis distances criterion in the stepwise method for variables' entry and removal. Approximately 10% of the locations (n = 68) from the black bear telemetry database were excluded from the habitat selection analysis in order to validate the model.

Expert model

Both expert habitat models were developed as weighted linear combinations of each models' layers (landscape and biophysical variables) obtained by a) expert opinion or b) review of the literature on black bear habitat requirements. With a weighted linear combination approach, the variables were combined by applying a weight to each followed by a summation of the results to yield a suitability map. This procedure is not uncommon in GIS and has a form similar to a regression equation (Eastman et al. 1995). Further, all GIS software systems provide the basic tools for evaluating such models. However, the main issues relate to the standardization of criteria scores and the development of the weights. To do this we used the pairwise comparison method developed by Saaty (1977) in the context of a decision-making process known as the Analytical Hierarchy Process (Eastman et al. 1995, Rao et al. 1991). The comparisons concern the relative importance of the two criteria involved in determining suitability for the stated objective, in this study, black bear habitat. Ratings were provided on a nine-point continuous scale, ranging from 1/9 (extremely less important) to 9 (extremely more important), and the midpoint 1 being equally important (see Eastman et al. 1995). In developing the weights, a group of individuals (minimum of two) compared every possible pairing and entered the ratings into a pairwise comparison matrix.

Opinion-based model. The expert opinion-based model required the collaboration of experts in assessing the importance of variables influencing black bear habitat selection in the study area. Two experts committed to developing the weights for the pairwise comparison matrix. Both investigators had a combined 47 years of experience studying black bears and their habitat in the Bow River Valley. We solicited input from the experts in regard to the variables selected for building the model and how the variables should be divided up for the pairwise comparion matrix. The experts preferred to score the variables by seasons relevant to the biological needs of bears: pre-berry (den exit to 15 July) and berry (15 July to den entry). Matrix scoring was done within the variables and among the variables. Five habitat variables were used in the analysis: elevation, slope, aspect, greenness, and distance to nearest drainage. The time required to perform the pairwise comparisons (n = 12) for both seasons was 90 minutes.

Literature-based model. Expert models based on data obtained from the literature were developed like the expert opinion models. We used the available literature on black bear habitat selection to help us weight the variables and completing the pairwise comparison matrices. One of the authors (APC) and two other biologists performed this task. We searched the literature to obtain as much information as possible on black bear habitat needs; preferably within our study area if possible. We scored the same variables in a pairwise comparison procedure as for the expert opinion model. All pairwise comparisons were carried out using the WEIGHT procedure in the Idrisi geographic analysis software (Eastman 1997). The 12 pairwise comparisons took 110 minutes to complete.

Linkage Zone Identification

The linkage analysis model was based on the assumption that the probability of a bear crossing a highway increases in areas where the highway bisects high quality bear habitat, and the highest probability of crossings occur in areas where topographic and landscape features are conducive to lateral, cross-valley movements.

To create the empirical black bear habitat model we used the GIS environment to apply the DFA findings to calculate the Mahalanobis distances for each pixel of the study area, and to calculate the posterior probabilities of group membership, i.e., a probability of good black bear habitat (Clark et al. 1993, Corsi et al. 1999). To allow statistical comparisons between the empirical and expert-based models, the latter being a habitat suitability index (HSI) type of model (U.S. Fish and Wildlife Service 1980 and 1981), we reclassified the continuous empirical habitat quality surface into 20 habitat favorability (or probability) classes, indexed from low (0%) to high (100%). We applied the same rules to the expert models. The reclassification process allowed us to describe the best black bear habitat as a percentage of the maximum habitat favorability value, regardless of the unit of measurement (a probability value or HSI-type score). Prime black bear habitat was defined as areas with habitat favorability values >70% for both models.

We used the GIS environment to generate four classes of highway crossing/habitat linkage zones:

- Class I – sections of TCH crossing prime black bear habitat extending up to 100m on both sides of the highway.
- Class II - sections of TCH crossing prime black bear habitat extending over 100m on both sides of the highway
- Class III - sections of TCH, ≥250m away from any permanent human development, nested within the Class II linkages, and within the areas conducive to cross-valley movement. This class was interactively mapped using the ortho-photographs and the DEM of the area.
- Class IV - sections of TCH not directly crossing the prime black bear habitat but having the prime black bear habitat within no more than 700m on both sides of the highway.

Data analysis

We tested each of the linkage models using a set of empirical black bear crossing and mortality points. Crossing locations were defined as the location on the TCH connecting a straight line between consecutive radiolocations on opposite sides of the road and obtained within 24 hours. Mortality locations came from the BNP wildlife mortality database (Banff National Park, unpublished data). We tested whether black bear empirical crossing and mortality points were randomly distributed with respect to their proximity to linkage zones. We generated random highway crossings, equal in size to the empirical data, and calculated the distances from both sets of points to the Class III and IV linkage zones. We repeated the calculations for each model. We used the kappa index of agreement (KIA) to measure the similarity between models and linkage areas (Campbell 1996). The KIA is a measure of association for two map layers having exactly the same number of categories. Indices range from 0.0 (no agreement) to 1.0 (spatially identical). Between map layers, values >0.75 indicate excellent agreement beyond chance; values between 0.4-0.75 demonstrate fair to good agreement; and values <0.4 indicate poor agreement (SPSS 1998). We used SPSS version 8.0 statistical package for all analyses (SPSS 1998). The software Idrisi was used to measure the KIA (Eastman 1997).

Multi-scale, Regional Movement Models

Habitat model

We modeled regional scale movements of four large mammals species (black bear, grizzly bear *U. arctos*, moose *Alces alces*, elk *Cervus elaphus*) and identified their potential linkage areas across the TCH. These species were selected: 1) because of their long ranging movement patterns and potential for interactions with transportation corridors in the study area (Woods 1991, Noss et al. 1996, Child 1998), 2) sufficient empirical location data were available to construct predictive spatial models of habitat suitability and 3) empirical crossing and mortality data were available to independently test the models.

To develop the habitat suitability models for the four species we first characterized their habitat using fifteen biophysical variables. Telemetry points were obtained from monitoring movements of the four species between 1980 and 2000 (Woods 1991, Hurd 1999; Gibeau 2000, M. Percy, unpublished data). Habitat suitability models were developed using a resource selection function as described earlier. We stratified the radiolocation data by the season (preberry [den emergence to 15 July] and berry [16 July to den entry] seasons for bears; summer [moose: May-October; elk: April-October] and winter [moose: November-April; elk: November-March] for ungulates).

Movement model

We based the movement component of the model on the least-cost movement principle and quantified the effects of slope angle and orientation (with respect to movement direction) on movement pathway. In mountainous areas, this principle is strongly affected by topography as it differentially influences effort required to move through space. We used the habitat probability surfaces for the habitat component of the movement model. In the absence of any empirical wildlife research we used an equation relating human walk time to the magnitude of slope angle in developing the topographic component:

$$Y = [-0.031((X^2)) - .025X + 1]^f$$

where X is the slope angle in degrees, Y is the walk time and f is a decay function relating the direction of the movement (with respect to the orientation of the slope) with change in an effort to move through space (Schneider and Robbins 1996).

We simulated the four species movement pathways by generating 11 potential entry and exit points located outside the Bow Valley and TCH transportation corridor. Entry and exit points were situated in high quality, valley bottom habitat, the most likely population source areas that animals would be expected to disperse from (Fig. 1).

We simulated movement pathways from selected combinations of entry and exit points in the regional study area. For any given pair of entry-exit points there were three iterations resulting in three different pathways. The first iteration simulates the least-cost movement pathway with no obstructions imposed. In the second iteration, the first pathway is blocked forcing the creation of a new pathway distinct from the original. In the third iteration, the first two pathways are blocked and an alternative route taken. These three distinct model runs can be thought of as producing the primary, secondary and tertiary movement pathways. This multiple iteration approach allowed a broad spectrum of potential movement pathways to be generated and quantified. For each species and season we simulated a minimum of 150 movement pathways and overall more than 1000 movement routes.

Highway crossing zone analysis

We examined the juxtaposition of the TCH with respect to the location of high quality habitat patches defined as areas with habitat probability classes exceeding 50 and 70 percent. We then extracted those sections of highway that dissect habitat patches extending more than 150m on both sides. For each of the mapped potential crossing zones we then calculated the number of zone intersections with simulated movement pathways, weighted by the crossing zone length.

Our method of identifying potential crossing zones often identified long sections of highway, which may be too generalized when recommending the placement of mitigating structures. We addressed this problem by modifying the model to analyze one-km long segments of highway. We sequentially numbered the segments starting from the eastern park boundary (east gate). Because the movement simulation is partially driven by the habitat quality aspect of the landscape, we considered this method equally valid in identifying potential wildlife movement, yet providing for better spatial resolution of the results. The maximum spatial resolution of the model, however, is not defined by adopting a specified length of highway, but by the resolution of the habitat and movement components of the movement simulation model. The questions we posed in this study were of regional scope and the length of the segments used in the analysis should reflect that. Given the 120m pixel size of habitat and topography layers and the obtained fit of the habitat models, we considered one kilometer to be the minimum segment length we could safely use.

Model testing

We tested the accuracy of highway crossing zones predicted by black bear and elk movement models with a set of empirical crossing and mortality points. There were too few crossing and mortality data from grizzly bears and moose to test their models. Empirical crossing locations were defined as described earlier for testing expert models; mortality locations were obtained from the BNP wildlife mortality database. Within the unfenced, unmitigated section of TCH we tested whether empirical crossing and mortality points were randomly distributed with respect to the distance to the predicted crossing zones created by the models. We generated a random set of highway crossings/mortalities equal in size to the empirical set and calculated the distances from both sets of points to the predicted wildlife crossing zones, individually per model stratified into 1) moderate-to-high and 2) high crossing frequency zone classes.

Within the fenced part of the TCH we assessed the congruence of current crossing structure placement with respect to the predicted regional movement patterns by plotting their location on the maps with the cumulative four species crossing frequencies by one-km segments. We also plotted their position on graphs showing this information with the total number of times the four large mammal species have been detected using the crossing structures during the last four years (Clevenger and Waltho 2000, A. Clevenger, unpublished data).

From the movement simulations, we identified the potential locations for highway mitigation, such as wildlife crossing structures, on the unfenced phase 3B section of TCH by plotting the pathway crossing frequencies by one-km TCH segments. We contrasted the predicted crossing frequency patterns on the mitigated (fenced) and unmitigated (unfenced) section of TCH, and examined the spatial pattern of high frequency predicted crossing zones.

Results and Discussion

Expert-Based Linkage Models

Empirical model

We generated the most parsimonious model by using eight variables. Overall, the DFA produced a sound statistical model. The high canonical correlation coefficient (0.755) indicated that the DFA was strong and discriminated well between the groups. Also, the Wilk's Lambda was low (0.43) denoting a relatively high discriminating power of DFA. The overall cross-validated classification accuracy was 87%. The model correctly classified 79% of the radiolocations into prime black bear habitat.

Model testing

Each of the linkage models was tested using a set of 37 empirical black bear crossing and mortality points. We found no statistical difference between the empirical crossings and random locations ($P > 0.05$), suggesting that Class IV linkages were a poor predictive tool for mapping cross-highway movement. There were significant differences between the distance from the empirical points and random locations to the Class III linkages. Empirical bear crossing and mortality locations were significantly closer to Class III linkages than expected by chance for the empirical model ($P = 0.018$), the expert opinion-based berry season model ($P = 0.027$), and the expert literature-based model ($P = 0.005$). Distances from the empirical points to the Class III linkages for the expert opinion-based pre-berry season model were not significantly different from the random locations ($P = 0.10$).

Of the Class III linkages, both seasonal expert opinion-based models had more linkage zones and were on average smaller in length compared to the empirical and expert literature-based model linkage zones (Table 1). When compared to the empirical model, there was a relatively strong correlation with the expert literature-based model (KIA = 0.662). The expert opinion-based pre-berry season and berry season models were only fair (0.416) to moderate (0.569) in agreement with the empirical model.

Table 1
Description of Class III linkages[a] of empirical and expert models.

Model	n	Minimum length (km)	Maximum length (km)	Total length (km)	Average length (km)
Empirical	11	0.20	2.70	8.6	0.78
Expert literature	9	0.30	1.90	6.3	0.70
Expert opinion Preberry	17	0.13	0.93	5.7	0.33
Expert opinion Berry	18	0.08	0.72	4.7	0.26

[a] Identified as segments of Trans-Canada highway (TCH) $\geq$250m away from any permanent human development, found within the Class II linkages and within the areas conducive to cross-valley movement. Class II linkages were segments of TCH crossing prime black bear habitat surpassing 100m on both sides of the road.

The expert literature-based model was most similar to the empirical model, both in the results of the statistical tests and the description of the Class III linkages. We compared the expert models and empirical model in terms of the level of juxtaposition of both the prime bear habitat maps and the Class II, III and IV linkage zones (Table 2). The expert literature-based model was consistently more similar to the empirical model than either of the two expert opinion-based models. Class III linkages for all three expert models had the greatest similarity with the empirical model. Among the expert models, the literature-based model had the strongest correlation with the empirical model. Expert opinion-based models ranged in KIA measures from 0.02-0.44, while expert literature-based models varied from 0.25-0.55.

Table 2
Kappa index of agreement[a] of the empirical black bear habitat model with expert opinion-based models and expert literature-based model.

Expert models	Empirical model		
	Class II[b]	Class III[b]	Class IV[b]
Expert literature	0.427	0.556	0.253
Expert opinion - Berry	0.368	0.379	0.362
Expert opinion - Preberry	0.324	0.441	0.027

[a] Measure of association for two map layers with exactly the same number of categories. Indices range from 0.0 (no agreement) to 1.0 (spatially identical) (Campbell 1996).
[b] See Table 1.

The most noteworthy result from the exercise was not the low performance of the expert opinion-based model, but the close proximity of the expert literature-based model to the empirical model. Our findings confirmed that the expert literature-based model was consistently more similar and conformed to the empirical model better than any of the expert opinion-based models. These results were based on the test of distribution of the empirical points from actual crossing and mortality locations in relation to the linkages, the descriptive characteristics of the Class III linkages, the measure of agreement between models, and measure of agreement between model linkage zones.

We explain the poor predictive power of the pre-berry expert opinion-based model being attributed to an overestimation of the importance of riparian habitat to the preberry habitat model, as compared to the opinions expressed in the literature. Another possible explanation is that the expert literature model is based on an analytical process (data collected, statistically analyzed and summarized), whereas the expert opinion model is based on information taken from how experts perceive attributes from memory and experience. Further, the fact that only 35% of the empirical black bear crossing and mortality locations were those of the preberry season may also have influenced how well it predicted linkage areas.

Multi-scale, Regional Movement Models

Habitat suitability models

Ten habitat suitability models were generated from the four species data sets. The overall cross-validated classification accuracies from the DFA and the habitat model validation tests using retained data suggest that all of the models showed a reasonably good fit with the empirical data. Overall cross-validated classification of models ranged from 66-86%. The median percent habitat probability value of tested points varied from 64-84%.

A noticeable feature of the grizzly bear berry season habitat probability maps was the assignment of the relatively low probability values to the Bow Valley and other major valleys in the study area. Although not a surprising result, this map contrasts with research that indicates valley bottoms to be of high value to grizzly bears (McLellan and Hovey 2001). We explain this discrepancy as a difference between the realized (actual use as influenced by human disturbance) and potential or unrestricted use of the landscape. We believe the distribution of aerial locations represents the former and better describes bear movements in the study area.

We could not produce a discriminating function to successfully separate grizzly bear preberry season aerial locations (canonical correlation = 0.05, cross-validated classification = 56%), therefore we focused on ground-based radiolocation data. We recognize the bias inherent with ground locations, however, compared to the spatially sparse aerial locations, ground locations more explicitly capture the pattern of habitat use around the linear infrastructures we investigated.

Model fit, sampling and uncertainties

When analyzed in conjunction with the distribution of the radiolocations used to build the discriminant functions, it becomes apparent that the predictive aspect of the nine models were inversely correlated with the spatial extents of the telemetry points, or conversely, the more spatially focused the points resulted in a higher fit of the resultant model ($R^2 = 0.658$).

The available radiolocation data more accurately depicted habitat use patterns and the locally important spatial variables were included in building the discriminant function. We recognize the apparent trade-off between the models. The theoretically more accurate, locally derived probability models may have less predictive power when applied on a regional scale, and the less accurate but more predictive regional models may be less predictive when applied locally. We considered our probability surfaces more than adequate for modeling regional-level wildlife movement patterns; however, we recommend caution if the models were to be applied to more localized issues.

Model testing and applications

Black bear and elk movement models were tested with a set of empirical crossing and mortality points. In the black bear model there was strong statistical evidence that the empirical bear crossing and mortality locations were closer to both high (Mann-Whitney U test, U = 390, $P = 0.009$) and moderate-high frequency crossing zones (U = 441, $P = 0.034$) than expected by chance. Similarly, empirical elk winter crossing and mortality locations were closer to the high frequency crossing zones than random points (U = 360, $P = 0.019$), but there was no difference between empirical points and the moderate-high frequency crossing zone locations ($P = 0.192$). We concluded that the model and empirical data correlated well.

We plotted the number of cumulative primary pathways and total pathways (primary, secondary and tertiary) in relation to the existing wildlife crossing structures. Primary pathway crossing frequencies on 0-24km of the TCH showed a close association with the empirical data for wildlife crossing structure use by the four large mammal species (Fig. 2A). The most prominent crossing locations were at 5-Mile, Cascade and East Gate underpasses. The Duthil underpass did not coincide well with the predicted crossings as there was more observed use than predicted use by the models. Predicted primary crossings were high in two locations without crossing structures: between Duthil and Powerhouse underpasses and in the Cascade area. We found a close association between total pathway crossing frequencies and observed crossing structure use on the same section of highway; however, it was not as strong as the primary pathway crossings (Fig. 2A). Greater predicted crossings than empirical crossings occurred at East Gate and Carrot Creek. High predicted total crossings in areas without crossing structures occurred between Duthil and Powerhouse underpasses, at Cascade, and west of Vermilion underpass.

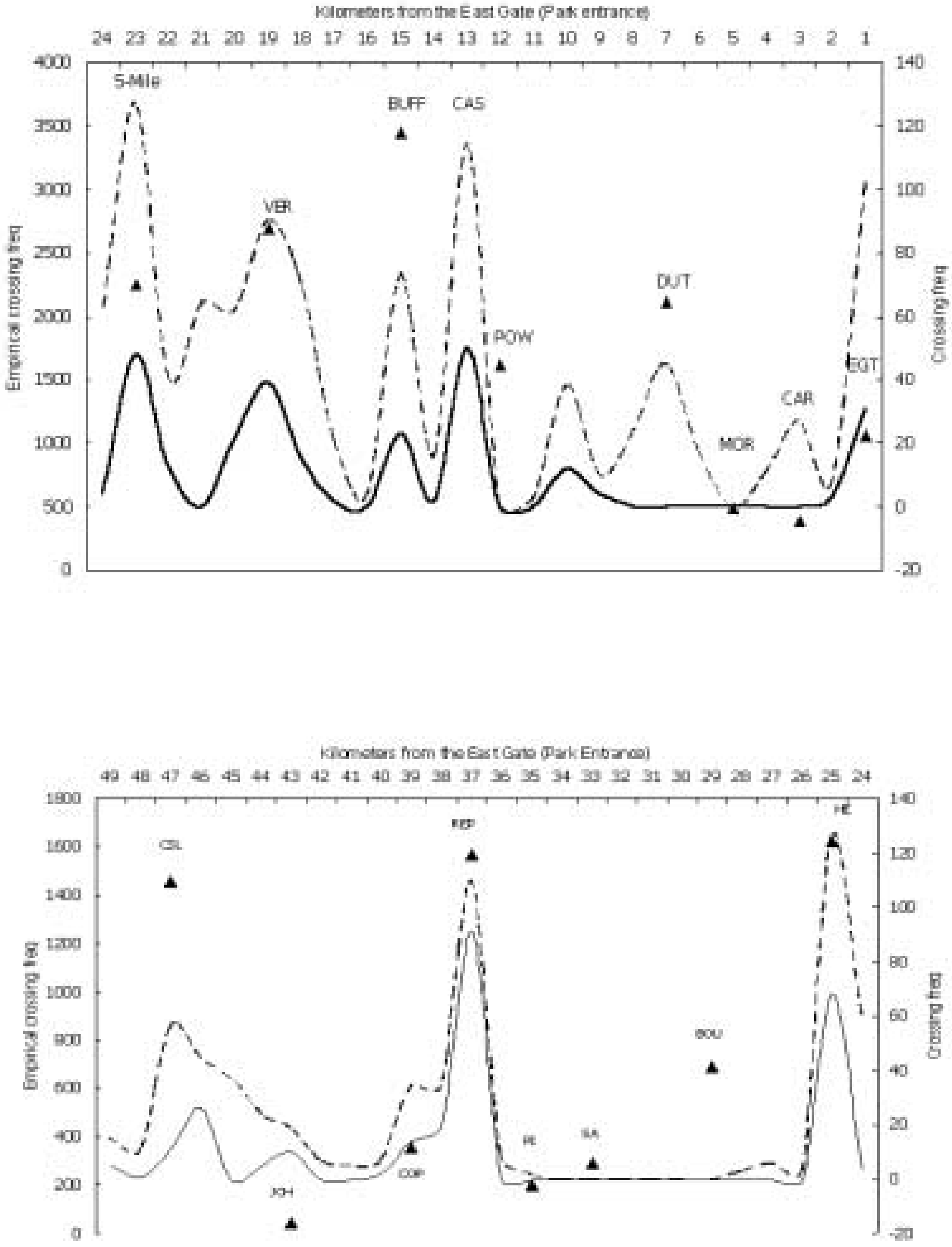

Fig. 2. The frequency of cumulative primary (solid line) and total pathways (intermittent line) in relation to empirical crossing data on wildlife crossing structure use on (A) 0-24km and (B) 25-50km, of the Trans-Canada highway in Banff National Park, Alberta. Wildlife crossing structures: EGT = East Gate, CAR = Carrot Creek, MOR = Morrison Coulee, DUT = Duthil, POW = Powerhouse, CAS = Cascade, BUFF = Buffalo, VER = Vermilion, 5-Mile = 5-Mile bridge, HE = Healy, BOU = Bourgeau, SA = Sawback, PI = Pilot, REP = Redearth overpass, COP = Copper, JOH = John, CSL = Castle.

Primary pathway crossing frequencies between 25-50km also showed a strong association with the empirical data for wildlife crossing structure use (Fig. 2B). There were no highway segments with greater predicted than empirical crossings, nor were there any high predicted crossings in areas without crossing structures. Total pathway crossing frequencies compared to crossing structure use were nearly identical to the primary pathway crossing frequencies. In the three crossing structure complex area comprised of Wolverine overpass, Wolverine and Bourgeau underpasses, there was a relatively high amount of passage by the four species although there were no predicted primary or total crossings. This suggests that the Wolverine overpass and other wildlife crossing structures can be functional and serve a vital purpose despite being located in an area with low expected highway crossings. There were no predicted crossings between Healy underpass and Redearth overpass. Thus, the lack of simulated pathways in this part of the valley might imply the highway is in a good location to minimize disturbance to wildlife movements.

The models identified several areas along the 0-50km mitigated section of highway that were outstanding in terms of their importance for wildlife movement. In order of importance, the highest predicted crossing areas based on the number of primary pathways were in the areas of Redearth overpass, Healy, Castle, Cascade underpasses and 5-Mile bridge. The number of total pathways were greatest at Healy, 5-Mile, Cascade and Redearth overpass. These predicted crossing locations were in agreement with the rank-ordered importance of wildlife crossing structures as indicated by usage by all wildlife species currently being monitored (A. Clevenger, unpublished data).

At the individual species level, the pattern of movement across the entire length of the TCH (0-86km) as predicted by the six individual species movement models (summer and winter included) was consistent, varied slightly, and overall was similar to that described above at the group level. To assess potential wildlife crossing structure placement along the unmitigated section of the TCH (50-86km) we weighted equally the four species and utilized the cumulative movement patterns generated by the models. We examined the intersection of primary and total pathways with the highway. Seven locations were indicated by high frequencies of predicted primary crossings across the highway (Fig. 3). The most prominent crossing locations were east and west adjacent to the Lake Louise townsite followed by highway 93 North junction and Wapta Lake. Nine locations were identified by the total predicted crossings on the highway. The greater number of pathways resulted in a finer resolution of key crossing zone locations and more of them. The average distance (± sd) between the nine locations was 3.3 ± 1.4 km.

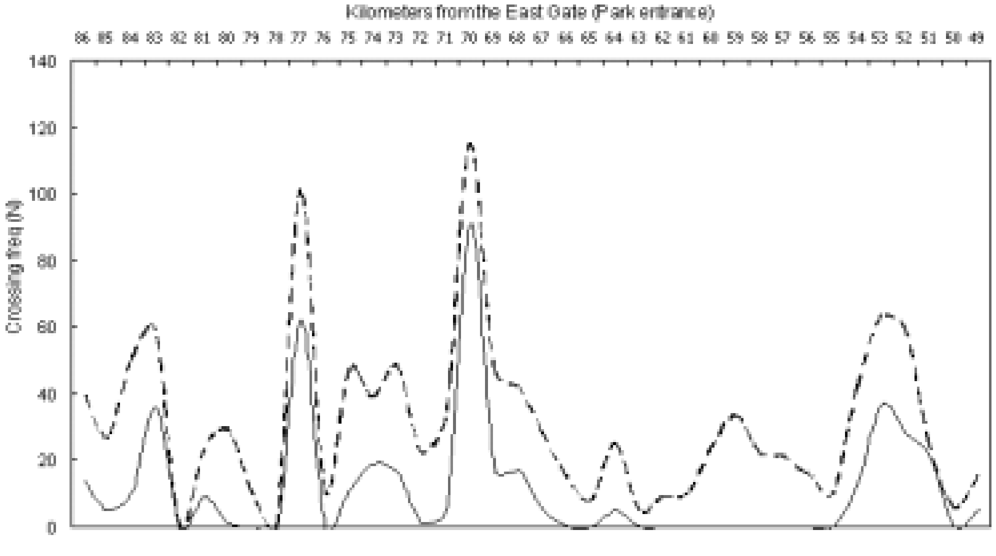

Fig. 3. Frequency and distribution of primary (solid line) and total pathways (intermittent line) generated by all movement models on the 50-86km, unmitigated phase of the Trans-Canada highway.

For comparative purposes we examined the intersection of primary and total pathways on the mitigated section of TCH (0-50km). There were a total of 13 locations indicated by high frequencies of predicted total crossings across the highway (Fig. 2A and 2B). Nine crossings were on phase 1 and 2, while four crossings were on phase 3A. The average distance (± sd) between the predicted crossing zone locations was greater on phase 3A (25-50km) than phase 1 and 2 (0-25km) (5.5 ± 5.0km vs. 2.7 ± 1.1km). The average distance between the 24 wildlife crossing structures on both phases is 2.1 ± 1.3km.

There are few methodological approaches to identify the placement of mitigation passages along road corridors and even less ways to determine spacing. Crossing structure placement has generally been related to location, i.e. riparian corridors, wildlife travel or migration routes (Reed et al. 1975, Evink 1996). Primary linkages across roads for key species such as large mammals may be spaced at wide intervals, many times wider than most small- and medium-sized terrestrial vertebrate home ranges. A variety of animals use wildlife crossing structures (Bekker et al. 1995, A. Clevenger, personal observation); however, passage planning based on our large mammal movement models would not represent the habitat connectivity needs of smaller fauna. Therefore, to enhance landscape connectivity for as many species and ecological processes as possible, we recommend that wildlife crossing structures be spaced at shorter intervals than indicated by our models.

We suggest a planning scheme that might consist of first, locating crossing structures in the area of key crossing zones as predicted by the models, and second, installing additional structures so that there is at least 1.5km between the crossing structures; this is a slightly shorter spacing between existing structures on the TCH. Our results also suggest that by providing additional crossing opportunities in areas not identified by the model output, the structures will be used if positioned and designed properly.

Conclusions

Expert-Based Linkage Models

There are several advantages to the expert-based techniques presented in our study. There are an assortment of GIS tools designed for model building purposes that are readily available today. GIS applications such as Idrisi (Clark University, Worcester, Massachusetts, USA), MapInfo Professional Software (MapInfo Corporation, Troy, New York, USA), and ArcView GIS (Environmental Systems Research Institute, Redlands, California, USA) are relatively inexpensive and easy to use. Idrisi has decision support procedures as a program module built into the geographic analysis system. Remotely sensed data, digital land cover data and habitat suitability maps are increasingly accessible, frequently updated and refined for individual users or government agencies. Further, empirical data from field studies of many wildlife species, particularly game species, are obtainable in most countries where road mitigation practices are implemented. The use of the Saaty's pairwise comparison matrix requires little training and ensures consistency in developing relative weights in the development of the expert-based models. This procedure is readily available in the Idrisi software package.

Identifying linkage areas across road corridors using both expert model types (opinion- and literature-based) we have presented can provide a useful tool for resource and transportation planners charged with determining the location of mitigation passages for wildlife when baseline information is lacking and when time constraints do not allow for pre-construction data collection. Regarding the latter, we spent approximately two months developing the four models. More than half of that time was dedicated to developing the more complex, data intensive empirical black bear habitat model. We do not advocate modeling linkage zones using exclusively expert information if empirical data are available. However, we do encourage others with empirical data for model building and testing to develop expert models concurrently so that their findings may be contrasted with ours.

Multi-scale, Regional Movement Models

We recognize the shortcomings of the movement models presented. Because of the large spatial scale (pixel size = 120m) our models were generalized and predicted crossing locations had a wide margin of error. Nevertheless, we feel they can be valuable tools for identifying locations of important bottlenecks or fracture zones at a regional scale. Once these are identified (as suggested above), smaller, local-scale features of the landscape, including possible wildlife concerns and engineering constraints, will need to be contemplated in order to select the most appropriate location for mitigation passages (Bekker 1998).

In this exercise we equally weighted the four species. However, some management strategies may give higher precedence to key species of conservation concern (Mills et al. 1993, Lambeck 1997). Adjustments can be made to the models by weighting individual species according to management priorities. An appropriate species weighting procedure is the pairwise comparison method (Saaty 1977, Eastman et al. 1995) shown earlier. Finally, we underscore the wide applicability of such models to other resource management and transportation planning issues, such as railways, trails, other road systems. The models could be applied to other human infrastructure, such as railways, trails, or other road systems.

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Biographical Sketch: Anthony Clevenger is currently directing a five-year research project addressing the ecological effects of roads on wildlife populations in the Central Canadian Rocky Mountains. The investigation focuses primarily on the Trans-Canada highway in Banff National Park, its permeability for wildlife, and effects in terms of wildlife mortality, movements, and habitat connectivity in the Bow River Valley. The study will be completed in April 2002.

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