Wildl. Biol. 17: 253-265 (2011)
DOI: 10.2981/09-051

www.wildlifebiology.com

Original article

Planning and prioritization strategies for phased highway mitigation using wildlife-vehicle collision data

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Mitigation measures to reduce wildlife-vehicle collisions (WVCs) on highways are becoming an established practice in many jurisdictions. Most highway mitigation projects occur while roads are being upgraded, enlarged or repaired. Many smaller highways may not be subject to these types of upgrades in the near future but are nonetheless problematic for causing WVCs. Thus, it is important to find cost effective ways to locate and prioritize stretches of highway for mitigation. We present several criteria that can be used to assist in prioritizing the location of wildlife-proof fencing along a 94-km stretch of road in one of Canada's National Parks. We considered temporal consistency of WVC occurrences, conservation value (i.e. reduction in WVC rates), economic benefits (i.e. cost of mitigation vs benefits in WVC reduction), and a combined approach to prioritize management actions. We compared the efficacy of four different lengths of fencing (i.e. phase lengths) at meeting these criteria: 2 km, 5 km, 10 km and 25 km. We used 1,244 WVC records from a long-tem monitoring program (1981-2005) as data to assess mitigation effectiveness. We found that longer fences best address conservation concerns, but all fencing sections, irrespective of length, rarely captured > 50% of WVC locations by species. We found that shorter fences were more economically efficient, but also more variable in performance, than longer fences. Lastly, we found that longer fence lengths tend to produce the best results for the combined metric criteria. Clearly defined management goals will determine the extent to which a phased approach to highway mitigation is viable.

Key words: collision, cost-benefit, fencing, hotspot, mortality, secondary highway, traffic

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Received 12 June 2009, accepted 5 May 2011

Associate Editor: Iain T. Gordon

Wildlife-vehicle collisions (WVCs) can be detrimental to animal populations and pose a significant risk to driver safety (Conover et al. 1995, Bruinderink & Hazebroek 1996, Seiler 2004, Ramp et al. 2005, Fahrig & Rytwinski 2009). Transportation and wildlife agencies are increasingly adopting highway mitigation measures in an effort to reduce WVCs (Romin & Bissonette 1996, Putman 1997, Beckmann et al. 2010). These measures may seek to modify driver behaviour (e.g. warning signs, speed reductions and animal detection systems), animal behaviour (e.g. reflectors and scent repellents), or physically block animal movement onto the road surface (e.g. fencing and rip-rap barriers) (Forman et al. 2003, Huijser et al. 2007b). The effectiveness of these approaches depends on the species involved as well as local topographical considerations (Putman 1997, Huijser et al. 2007b, Beckmann et al. 2010). Consequently, choosing target species and an appropriate location for the installation of mitigation measures are of primary concern to many transportation and wildlife agencies.

Siting mitigation measures requires at least two things: the necessary resources to construct mitigation (e.g. access to financing, permits/legislation and technology) and clearly defined management goals to set the targets for outcomes (e.g. an 80% reduction in ungulate vehicle collisions). Ideally, adequate resources will be made available once management goals have been defined. The reality of transportation and wildlife management is that budgets are not infinite and that management goals are set by a framework imposed by the availability of institutional resources (McGuire & Morrall 2000). Consequently, mitigating an entire highway is not an option for many agencies and managers must, in turn, make compromises. Compromise necessitates the optimization of available resources.

In our paper, we highlight a process of optimization for siting mitigation measures along a highway with a common, restrictive institutional framework. These restrictions include: 1) the requirement to synchronize installation of mitigation measures with the construction schedule of other highway maintenance operations, 2) a relatively uniform distribution of WVCs and 3) limited funding allocation relative to other highways in our area.

Highway mitigation is normally carried out during the construction of major highway upgrades such as twinning (two to four lanes), bridge replacement or resurfacing. These construction activities most often occur in phases as funding becomes available or as seasonal changes limit construction schedules. Mitigation measures incorporated into other construction activities along the highway must therefore follow this phasic sequence. For example, the four main phases of mitigation construction along the Trans-Canada Highway in Banff National Park, Alberta, occurred sequentially, from east to west, during lane-twinning. These phases included Phase 1 (1982-1985: 11 km), Phase 2 (1986-1988: 16 km), Phase 3A (1995-1997: 18 km), and Phase 3B (2008-2012: 30 km) (Clevenger et al. 2002b, Ford et al. 2010). It has taken almost 40 years, excluding environmental assessments, to complete about 75 km of highway mitigation on this stretch of highway in Banff. Prioritizing phases for mitigation may help to optimize available resources if WVCs occur in predictable and localized areas.

Choosing where to site phased mitigation measures will be relatively straightforward if WVCs are clustered in space and predictable over time. For example, a mass mitigation of tiger salamander *Ambystoma tigrinum* between a wetland and upland site intersected the Trans-Canada Highway, Alberta, in the late 1990s. This prompted an *ad hoc* intervention involving drift fences, pit fall traps and monitoring. This response was made possible, in part, by the limited spatial scale over which this event occurred (Clevenger et al. 2001b). In other situations, WVCs are more uniformly distributed along a highway and more unpredictable in time. Under these conditions, it becomes increasingly difficult to determine where to site mitigation measures in a way that will minimize WVCs. One approach is to identify target species that have a more clustered distribution of WVCs than the broader assemblage of species in the management area. Mitigation can then be targeted towards species that: 1) pose the greatest risk to human life and property, 2) are reliably found in the same areas over many years, 3) have important roles in ecosystem function, 4) are rare in the area, or 5) are abundant in the area. Even after the management goal has been identified and the species targeted, there remains a need to mobilize resources to support even modest management interventions.

Funding allocations for road improvements, at least in our study area, are weighted towards those highways with the highest traffic volumes. However, secondary or low-volume roads can also pose a major threat to wildlife. These roads typically contain $<$ 5,000 average annual daily traffic (AADT), are two-lanes wide, and pass through largely rural and peri-urban areas. Across North America and Europe, increasing WVCs are a result of growing traffic volumes on secondary highways due to urban sprawl and increased commuter traffic (Kline & Swann 1998, Hansen & Brown 2005, Ramp et al. 2005). These roads are unlikely to be the focus of costly mitigation such as wildlife crossing structures typically installed on major highways (McGuire & Morrall 2000, Marshik et al. 2001, Evink 2002, Wagner 2006). To our knowledge, there are few examples of major mitigation interventions on secondary roads (but see Land & Lotz 1996). There is a clear need to develop analytical tools that will help managers identify and prioritize locations for mitigation solutions in a cost-effective manner on low traffic volume highways.

In our paper, we focus on the mitigation of low-volume highways and the use of wildlife-proof fencing to prevent large mammals from accessing the highway right-of-way (Clevenger et al. 2001a, Dodd et al. 2007, Huijser et al. 2007b). We developed four criteria to prioritize species and then site fencing. We used temporal consistency as a measure to evaluate species-specific WVC rates over time, irrespective of location along the highway. This criterion does not address the absolute abundance or spatial distribution of species-specific WVC rates. Rather, this criterion allows us to determine which species are consistently involved in vehicle collisions over time. The remaining three criteria specifically address the spatial aspects of mitigation: conservation value, net economic benefit and a combined economic-conservation metric. The conservation value criterion identifies the location that maximizes WVC rate reduction. The net economic benefit criterion minimizes the ratio of mitigation costs to societal level benefits accruing from WVC reduction. The combined metric, hereafter referred to as the mitigation-effectiveness index, weights both conservation and economic criteria equally, thus optimizing WVC reductions and economic benefits. Our overall goal is to determine the optimal location and extent of fencing based on these criteria evaluated among four different phase (fence) lengths.

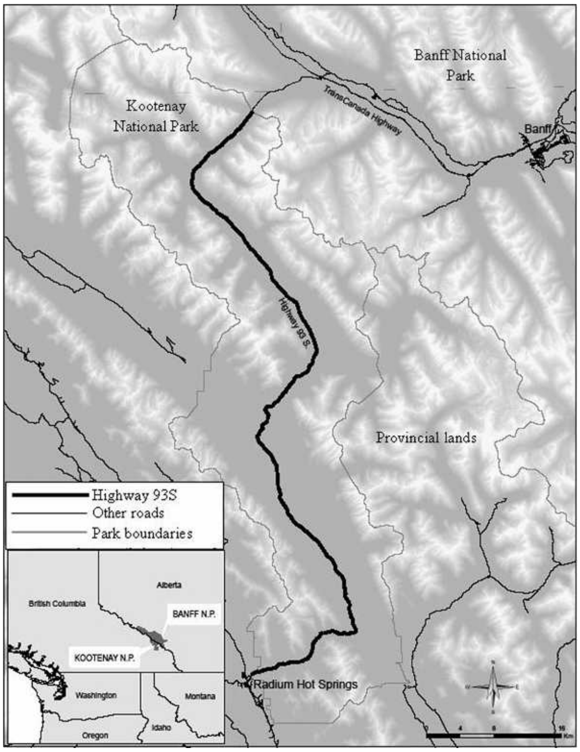

Figure 1. Our study area showing Highway 93S and other roads in Kootenay National Park, Canada.

Material and methods

Study area

Our study area was located in Kootenay National Park (KNP), British Columbia (B.C.), Canada. KNP is approximately 1,406 km^2 in area and is bordered by Banff National Park and Yoho National Park to the east and northwest, respectively, and British Columbia provincial lands to the west and south (Fig. 1). KNP is located on the western slopes of the Rocky Mountains with a climate characterized by long, cold and wet winters and short summers (Achuff et al. 1984). Major ecosystems in the park include montane, subalpine and alpine, with the montane ecosystem occurring at the lowest elevations and primarily valley bottoms. The majority of the park is forested (Douglas fir *Pseudotsuga menziesii*, lodgepole pine *Pinus contorta* and white spruce *Picea glauca* at lower elevations and subalpine fir *Abies lasiocarpa* and Engelmann spruce *Picea engelmannii* at higher elevations) although shrub and grass meadows occur in the valley bottoms, and recent forest fires have altered habitat in much of the northern half of the park.

KNP was established in 1920 through an inter-governmental agreement whereby the federal government would fund the construction of a road, later known as Highway 93 South (93S), from Banff National Park to Invermere, B.C., in exchange for 8 km of land on either side of the road. Thus, KNP was bisected by a road from its inception as a protected area. Highway 93S follows along the valley bottom and parallels major rivers (i.e. Vermilion and Kootenay Rivers) in KNP. The highway is paved, two-lanes wide, with occasional passing lanes and has a posted speed limit of 90 km/hour. The length of the highway in KNP is 94 km, although a 9 km section of 93S continues north into Banff National Park. For the purpose of this analysis, 93S will refer to the section within KNP.

Rapidly expanding human populations in Alberta and B.C., along with growing recreational interest in nearby areas, are increasing traffic volumes on 93S. The communities of Radium Hot Springs and Invermere, B.C., near the south end of KNP, are visited by a growing number of tourists and are experiencing rapid growth in the resort home market for Alberta residents. Between 2005 and 2006, Radium Hot Springs had the highest population growth rate (13.3%) of 157 B.C.

communities, while nearby Invermere ranked third (6.6%; BC Stats 2006).

The growth in human communities adjacent to KNP has led to increased traffic volumes on 93S, with projected increases into the future. AADT increased from approximately 1,450 in 1982-1984 to 1,650 in 1987 (Poll 1989). More recently, traffic increased from 1,900 AADT in 1997 to 2,300 AADT in 2004 (Parks Canada Agency, unpubl. data). A large part of the traffic is recreationally-driven and occurs during the summer months. Large commercial trucks are allowed to use 93S and traffic classifier data from 1987 estimated that large trucks comprised 5% of the total traffic volume in July and 13% in November-December (Poll 1989). Large trucks appear to be responsible for a disproportionate number of WVCs, in part due to the greater prevalence of truck traffic during early morning periods when large animals may be more active (Poll 1989).

Data collection

WVC data are maintained in a Parks Canada database (Parks Canada Agency, unpubl. data). When a WVC is reported or a carcass is opportunistically found along the roadside, Parks Canada staff obtain geographic coordinates with handheld Global Positioning System units (± 5 m accuracy) and record species, age, sex, and occasionally, physiological condition of the carcass. Older WVC data (pre-1995) may have spatial error up to 800 m (Clevenger et al. 2002b) as these data were commonly referenced to nearby landmarks (e.g. "200 m from Marble Canyon"). Nonetheless, Parks Canada has gone through considerable efforts to ensure that the data are accurate (A. Dibb, pers. obs.). Coordinates were compared to location descriptions and where there were discrepancies, observers were reinterviewed to resolve any potential errors.

Data analysis

We classified species into groups when WVCs for individual species were low (Table 1). Additionally, some deer carcasses were not identified to the species level, so we included all known and unknown deer species into a single category 'all deer species'. To assess the temporal consistency of each species group, we classified WVCs along our entire study area into one of five, 5-year classes (i.e. 1981-1985, 1986-1990, 1991-1995, 1996-2000 and 2001-2005), and analyzed WVC counts per year-class as the response variable with the null hypothesis that WVCs are consistent over time. We chose to use a χ^2 goodness-of-fit test rather than other trend analysis techniques (e.g. autoregression). The reasons were to ensure adequate replication among years, to minimize temporal autocorrelation, because changes in species counts over time tend to be non-linear for most species, and because we are using count data.

Table 1. Composition of species groupings used in our study.

Species group	Species
All deer species	*Odocoileus* spp.
Bears	*Ursus arctos, U. americanus*
Coyote	*Canis latrans*
Elk	*Cervus elaphus*
Felids	*Lynx rufus, L. canadensis, Felis concolor*
Goat	*Oreamnos americanus*
Moose	*Alces alces*
Mule deer	*Odocoileus hemionus*
Bighorn sheep	*Ovis canadensis*
Wolf	*Canis lupus*
White-tailed deer	*Odocoileus virginianus*

To assess the spatial distribution of WVCs within the context of realistic lengths of highway that could be considered for mitigation, we created hypothetical, continuous fence lengths of 2 km, 5 km, 10 km and 25 km. We chose these lengths because they represent a realistic range based on past experience with engineering and budget issues among highways in other parts of North America and in adjacent Banff National Park (McGuire & Morrall 2000, Dodd et al. 2007, Giles et al. 2010). To help minimize the effect of spatial error on our analysis, we divided the highway into 1 km-long sections and assigned each WVC location to its appropriate section (Bissonette 2007, Gunson et al. 2009). Each fence length was then overlaid along each 1-km section of the highway, starting at the northern end of our study area and 'moving' the fence sequentially south, 1-km section by 1-km section, until the southern terminus of the fence coincided with the southern end of the highway. WVC records for all 1-km fence sections were summed along 93S for each fence length and location.

We then developed three criteria to evaluate the effectiveness of fence location: conservation value, net economic benefit and a mitigation-effectiveness index. The optimal location of fencing for conservation value maximizes WVC reduction for a given species group. To calculate fencing performance under the conservation value criterion, we wanted to know the proportion of WVCs contained within each fence section at each location, by species group, and if this value was greater than expected when compared to a uniform distribution of WVCs along the highway. If WVCs are distributed uniformly along the highway, then each fence location would account for a proportion of WVCs equal to the proportion of the 94 km-long highway it occupies (i.e. 2, 5, 11 and 27% of total WVCs per species group for fences 2 km, 5 km, 10 km and 25 km long, respectively). Expected values are species group specific for each fence length. For example, under the null model of uniformity, a 2-km fence section should contain 2%, or two WVCs, for Species A if that species has a total of 100 WVCs along the entire highway. Likewise, Species B, with 400 WVCs, would have an expected value of eight WVCs for each 2-km section. Using species group as the replicate ($N = 8$, see Table 1), we compared the expected values with both the mean and maximum WVCs per fence location using a Wilcoxon sign ranks test. We analyzed each fence length separately and only used the 'all deer sp.' group rather than analysing each deer species separately.

To evaluate the economic benefit of fencing, we calculated the ratio of fencing costs to the benefit, in dollars ($US), of WVC reductions. Recent mitigation on the Trans-Canada Highway in Banff National Park (Phase 3B) has provided us with cost figures for fencing along similar terrain and within the Parks Canada Agency at $US 75/meter for one side of the highway (T. McGuire, pers. comm.). The fencing is 2.4-m high woven-wire, with wooden posts, variable dimension mesh and a 1-m buried apron of chain-link fence material (Fig. 2). We did not adjust for inflation nor did we incorporate maintenance costs into the equation for calculating fence costs (but see Huisjer et al. 2009 for a more thorough treatment of these factors).

The benefit of fencing was determined by first summing the total number of ungulate WVCs within each fence location and for each fence length. This value provides an indication of mitigation effectiveness had fencing been installed at the start of the monitoring effort (1981). We then reduced the actual number of WVCs per location by a conservative 20% to account for potential fence intrusions by wildlife (Clevenger et al. 2001a). Each WVC per fence location and length was then multiplied by a species-specific cost per WVC, based on Huijser et al. (2009). This cost represents damage to property, human health and lost recreation value of the animal. Huijser et al. (2009) included hunting opportunities within their recreational values. Hunting is not allowed within KNP, but we suggest this value is an adequate proxy for wildlife viewing opportunities within this national park. Furthermore, wildlife from KNP may move outside of the park boundaries where they can be legally hunted (A. Dibb, pers. obs.). Husijer et al. (2009) reported the costs of a WVC for deer *Odocoileus* spp. ($US 6,617), elk *Cervus elaphus* ($US 17,483) and moose *Alces alces* ($US

Figure 2. An elk grazes next to a wildlife-exclusion fence near the Trans-Canada Highway in Banff National Park, Alberta. Proposed fencing design and habitat in our study is similar to the photo.

30,760). We used the value for deer presented by Huijser et al. (2009) for bighorn sheep *Ovis canadensis,* because these two species are comparable in body size and so would pose a similar risk to human health and property in the event of a WVC. This is also a conservative estimate for bighorn sheep in our study area because the economic cost of mortality is greater than deer owing to the viewing (within the park) and hunting (in nearby provincial lands) value of bighorn sheep.

The total cost of WVCs among these four ungulate species within each fence length and location was summed. For all four fence lengths and locations, we divided the cost of each fence (2 x $US 75/m) by the benefit of WVC reduction, expressed as a ratio. A ratio of $<$ 1 means that fencing provides a net loss to society, relative to WVC costs, whereas a ratio $>$ 1 indicates that fencing reduces the overall WVC costs for that fence length. We compared the highest (best performing) 20 ratios of each fence length and location to determine which length tends to have the greatest performance using the cost:benefit ratio as the response variable and fence length as the predictor with a Kruskal-Wallis test. We chose the top 20 performing locations as a cut-off because transportation practitioners would not likely plan for mitigation in areas below this performance level (A. Dibb, pers. obs.).

To create the mitigation-effectiveness index, we combined the conservation criterion with the net economic benefit criterion to determine the location and length of fencing that maximizes both objectives equally. In this case, we selected only ungulate species (deer, elk, moose and bighorn sheep) from the conservation criterion to make this analysis comparable to the economic analysis described above. To combine these two criteria, we first ranked the total number of ungulate collisions per fence, with lower ranks indicating more collisions per location. We then ranked the cost:benefit ratio of each fence, with lower ranks assigned to greater economic benefit. We then calculated the mean rank for both the conservation and economic ranks for each fence location and length. Lastly, we took the inverse value of this measure, so that increasing values of the mitigation-effectiveness index corresponded to increasing levels of fencing performance (i.e. greater optimization). We selected the top 20 mitigation-effectiveness index values and compared the representation of fence lengths within this selection using a Kruskal-Wallis test, with fence length as the predictor variable. Lastly, we summarized the geographic locations of the three top-ranked fence lengths for each performance criteria.

Results

WVCs involving ungulates were most common during our study, representing 84% of 1,244 WVCs on Highway 93S between 1981 and 2005. Bears *Ursus* spp. were the most common large carnivore in WVCs, representing 75% of the carnivore species group (bears, wolves *Canis lupus*, felids (cougar *Felis concolor,* Canadian lynx *Lynx canadensis* and bobcat *L. rufus*)). Most species showed significant variation in mortality rate among year classes, with

Table 2. Inter-year variation in wildlife-vehicle collisions, expressed as a percent of total collisions per species from 1981 to 2005, along Highway 93S, Kootenay National Park, Canada. When analysis was not available because of low replication within some year classes, it is indicated by na. χ^2 were derived from the count data. Proportion data are shown here for ease of interpretation.

	Year group (% of N)							
Species group	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	N	χ^2	P
All deer species	18	23	23	16	20	595	11.45	0.022
Bears	12	16	22	29	20	49	3.76	0.44
Coyote	17	33	22	15	13	60	7.83	0.098
Elk	43	30	18	5	4	279	153.53	$<$ 0.0001
Felids	0	25	0	50	25	4	na	na
Goat	0	0	0	33	67	3	na	na
Moose	11	24	19	13	33	96	15.56	0.004
Mule deer	25	39	14	12	10	113	32.71	$<$ 0.0001
Sheep	19	23	21	19	19	53	3.02	0.99
Wolves	0	23	23	46	8	13	na	na
White-tailed deer	9	25	24	15	28	454	55.63	$<$ 0.0001

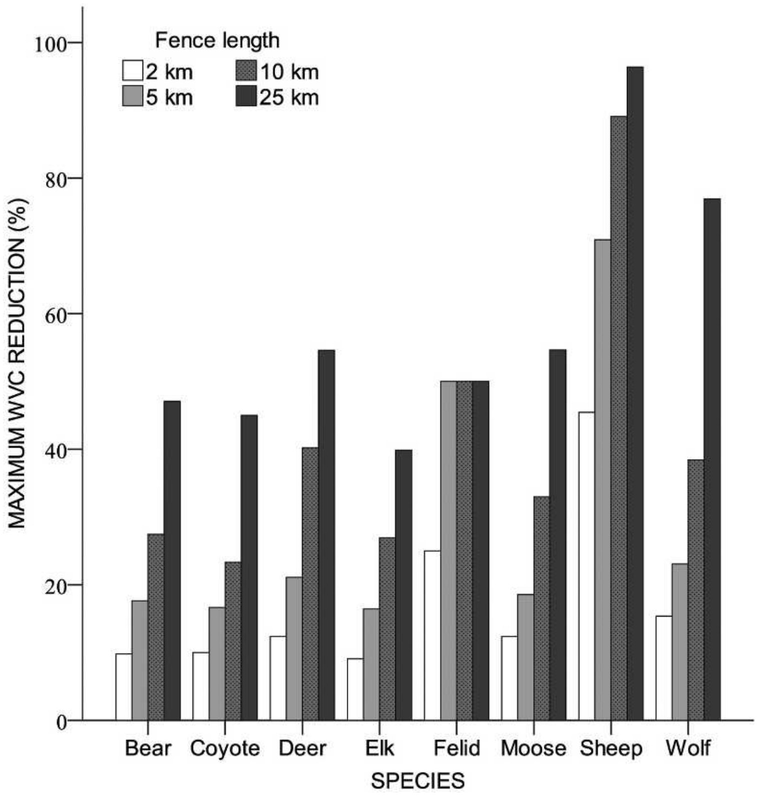

Figure 3. Maximum wildlife vehicle collision (WVC) density for a single fence section, expressed as a percentage of total WVC for each species.

elk showing a notable decreasing trend (Table 2). Deer and sheep probably represent the greatest potential for focusing mitigation efforts when it comes to total WVC reduction because they are consistently represented in WVC incidents over time and have a high relative frequency of occurrence in each year class.

The maximum potential reduction in WVC varied widely among species, between 9 and 50%, 16 and 71%, 23 and 83%, and 40 and 100%, for 2, 5, 10 and 25 km fence lengths, respectively (Fig. 3). This indicates that WVC locations are not generalized across species. For all large mammal species combined, the best performing fence locations increased from 7% to 42% WVC reduction between 2-km and 25-km lengths, respectively. Bighorn sheep and wolves have the greatest potential WVC reductions indicating highly clustered distributions. Bear, elk and coyote *Canis latrans* collisions showed some clustering, but these species had the lowest potential for WVC reductions within a given fence location, indicating that WVCs for these species tend to be more uniformly distributed along 93S. Among species groups, the maximum and mean WVC frequency per fence location was greater than expected when compared to a uniform distribution of WVCs along the highway (Table 3), with two exceptions. The mean WVC per fence location was not significantly different from a uniform distribution for the 10-km or the 25-km fence length.

Table 3. Paired t-tests comparing the distribution of mean and maximum wildlife vehicle collisions (WVC) per fence section for each species group, where species group is the replicate (df=7 in all tests). Mean difference < 0 means that more WVCs occurred than expected, and a mean difference > 0 means that less WVCs occurred than expected.

	Fence length (km)											
	2			5			10			25		
	Mean difference	Z	P	Mean difference	Z	P	Mean difference	Z	P	Mean difference	Z	P
Maximum	-15.560	-2.52	0.012	-24.338	-2.521	0.012	-37.925	-2.521	0.012	-37.2088	-2.521	0.012
Mean	-0.205	-2.52	0.012	-0.0548	-2.521	0.012	0.338	-0.560	0.575	-0.9739	-0.840	0.401

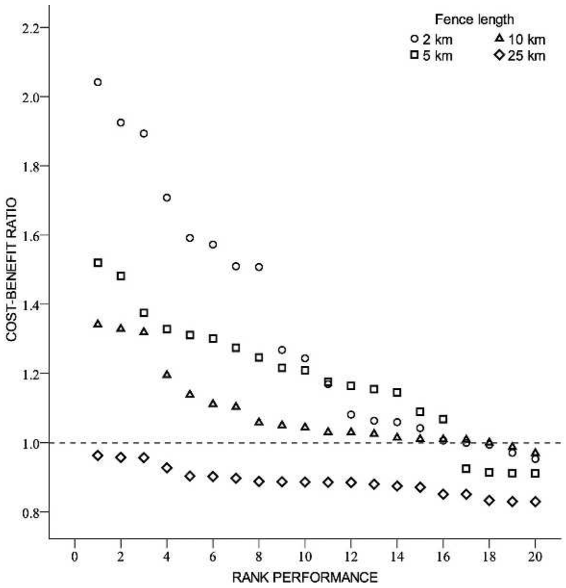

Figure 4. Comparison of top 20 best-performing cost:benefit ratios between fence length groups along Highway 93S, Kootenay National Park, Canada. The horizontal line indicates the cost recovery point, where values below the line are a net-loss and values above the line are a net-gain.

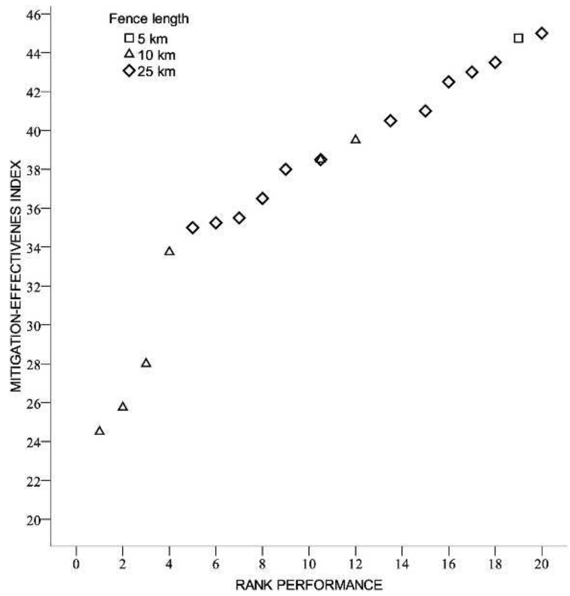

Figure 5. Comparison of top 20 ranking fence length groups based on their mitigation-effectiveness index value along Highway 93S, Kootenay National Park, Canada. The index value decreases with greater performance. 2-km fence lengths did not rank within the top 20 index values.

The net economic benefit criterion was best achieved by shorter fence lengths (Fig. 4). Fence length significantly affected the cost:benefit ratio among the 20 top ranking fence locations ($\chi^2=44.26$, df $= 3$, $P < 0.0001$), with performance decreasing inversely with fence length. Ranking the cost:benefit values for all fence sections suggested that 40% of the top 20 fence sections were 2 km, 44% were 5 km and 16% were 10 km long. The top ranked 25 km long fence section was 56th among all fence sections as measured by the net economic benefit criterion.

The 10-km fence length had the highest mitigation-effectiveness index, yet most of the top 20 performing fence locations were 25-km long sections (Fig. 5). Only one 5-km section occurred within the top 20 best performing sections, and there were no 2-km long sections as measured by the mitigation-effectiveness index.

Clear patterns emerged with regard to the location of each top-ranked fence length for all three criteria (Table 4). For the conservation value criterion, 25-km lengths starting near kilometer marker 44 and finishing near kilometer marker 73 would capture most WVCs of any fence length along Highway 93S. Fencing in these areas would also encapsulate the top performing 2-km, 5-km and 10-km sections when looking at the conservation value criterion. Specifically, for 2-km, 5-km and 10-km fence lengths, locations starting near kilometer marker 50 and ending near kilometer marker 60 had the greatest performance. Further, a 2-km section starting at kilometer marker 87 and a 5-km section starting at kilometer marker 84 also ranked high, suggesting a localized WVC hotspot at the southern end of KNP. Location of the best-performing mitigation-effectiveness index sections closely followed the performance of the net economic benefit criteria for the 2-km sections and was identical to the conservation value criteria for 5-km and 10-km sections.

Discussion

Highway mitigation is most likely to occur if transportation and wildlife agencies can demonstrate tangible benefits of their infrastructure investments. Our method of describing WVC distribution using a 'moving fence' technique has provided valuable insight into the potential benefits and limitations of mitigating a localized section of low-volume highway. Our research has found that the optimal location and extent of mitigation depends on whether temporal, economic or WVC reduction *per se* takes precedence.

Table 4. Location of the top three performing fence sections as measured by the conservation value, cost:benefit and mitigation-effectiveness index criteria for fence lengths 2-km, 5-km, 10-km and 25-km, Kootenay National Park, British Columbia, 1981-2005. * indicates a tied ranking.

		Conservation value		Cost:benefit		Mitigation effectiveness	
Fence length	Ranking by fence length	Km section (Start-end)	WVCs	Km section (Start-end)	Ratio	Km section (Start-end)	Index
2	1	52-54	85	87-89	2.04	52-54	0.0157
	2	58-60	75	52-54	1.93	58-60	0.0139
	3	57-59	74	58-60	1.89	87-89	0.0136
5	1	56-61	156	56-61	1.52	56-61	0.0223
	2	57-62	149	57-62	1.48	57-62	0.0206
	3	55-60	144	84-89	1.38	55-60	0.0192
10	1	51-61	287	51-61	1.34	51-61	0.0408
	2	52-62	285	52-62	1.33	52-62	0.0388
	3	50-60	279	50-60	1.32	50-60	0.0357
25	1	46-71	467	36-61	0.96	38-63	0.0286
	2	47-72	464	37-62	0.96	37-62	0.0284
	3*	44-69	461	38-63	0.96	46-71	0.0282
		45-70					
		48-73					

We found significant fluctuations in the temporal distribution of WVCs for most species. These changes may be related to demographic processes, such as changes in the population size of different species over time (Baker et al. 2004, Seiler 2004). For example, elk showed an obvious decline in WVCs from the early 1980s when almost half of all WVCs for this species occurred. This trend may be explained by a number of factors including population decline caused by WVCs (Poll 1989) or large scale habitat changes due to historical fire suppression regimes within KNP that have reduced elk habitat quality (White et al. 1998). In the summer of 2003, large wild fires (> 15,000 ha) occurred in some areas of KNP, and this will likely change the distribution of high quality habitat for species such as elk and grizzly bear *Ursus arctos*. This in turn may not only affect the population densities for some species, but also shift the spatial distribution of WVCs (Joyce & Mahoney 2001). Other species, such as white-tailed deer showed significant changes in WVCs between year classes, yet there was no discernable trend. Other species, such as bighorn sheep and bears, had fairly consistent WVC frequencies over time, suggesting these species may be ideal candidates for targeted mitigation efforts.

At local spatial scales (2-5 km), we found that WVCs were not uniformly distributed along the highway, as was found elsewhere (Hubbard et al. 2000, Malo et al. 2004, Ramp et al. 2005). The mean WVC rates among species were greater than expected for 2-km and 5-km long sections, but not for longer fence sections. On the other hand, the maximum potential WVC reduction was greater than expected by chance for all fence lengths. However, maximum potential reduction of WVCs, even for the 25-km fence sections, was only about half of the total WVCs per species group for most species. Conversely, Clevenger et al. (2001a) found that fencing was > 80% effective at reducing WVCs along a nearby continuous 45-km section of high-volume highway. Our finding suggests that phased mitigation up to 25 km in length may not be a viable means of reducing the additive effects of road mortality beyond > 50% for most wildlife populations in KNP, with one notable exception. WVC clustering was high for bighorn sheep, which is likely a function of their highly localized habitat preference in our area. Bighorn sheep are of particular interest to local managers given their impacts on motorist safety (relative to smaller wildlife) and contribution to KNP management objectives related to maintaining wildlife viewing opportunities (A. Dibb, pers. obs.). These management goals, combined with the predicted effectiveness of fencing towards a reduction in sheep vehicle collisions, and the relatively consistent occurrence of sheep mortalities over time suggests that this is an ideal focal species for mitigation planning in our study area.

From an economic perspective, shorter fence lengths tended to outperform longer fence lengths.

Variability in WVC density increases over increasing distance, such that shorter fence lengths can more efficiently target local concentrations of WVCs. At the same time, the variability in performance between fence locations of the same length is greater with shorter fence sections. That is, the probability of 'missing' the true WVC hotspot is higher with shorter fence lengths. The sensitivity of shorter fence lengths to spatial error in WVC data stresses the importance of collecting accurate and systematic road mortality data (Huijser et al. 2007a, Gunson et al. 2009). Ensuring that consistent and accurate data collection protocols are followed can greatly improve the planning and performance of highway mitigation measures (Bissonette 2007, Gunson et al. 2009).

When optimizing conservation and economic criteria (i.e. the mitigation-effectiveness criterion), 10-km fence lengths were the most effective for ungulates in our study area. Our results showed that longer fence lengths were better at reducing WVCs, while shorter fence lengths maximized net economic benefits. Therefore, it is understandable how a mid-length fence section would optimize these criteria. The 2-km and 5-km fence lengths did not perform well in this regard, due in large part to their limited potential to reduce WVCs compared to longer fence lengths. Again, this likely results from the relatively homogenous distribution of WVCs of most ungulates along 93S.

The consistency of the best-performing fence section locations (kilometer markers 50-60) among all criteria suggests that mitigating this area of Highway 93S will provide the most benefits, with a 2-km fence length providing the greatest economic return, a 25-km long section providing the greatest decrease in WVC, and a 10-km fence length providing the best combined conservation and economic benefit.

There are at least four major caveats we see in the interpretation of our results. First, the mitigation-effectiveness index we used here could be improved through additional weightings and factors. For example, highway mitigation projects have not only attempted to improve motorist safety and reduce WVC among wildlife populations, but maintain landscape connectivity by using wildlife crossing structures (Clevenger & Waltho 2000, 2005, Dodd et al. 2004, Olsson & Widen 2008). Determining the placement of crossing structures may include habitat, topographic and highway design considerations, all of which could be added into an analysis to further weight the criteria. Furthermore, given that WVC locations are not necessarily the same areas where animals cross roads safely, supplementing WVC data with data from animal movements (e.g. radio-telemetry and snowtracking) can improve mitigation placement (Clevenger & Huijser 2011).

Second, installing fences along areas where WVCs are problematic will not eliminate all WVCs within the area. Mitigation fencing can displace animal movement from former WVC hotspots towards fence ends. We attempted to address this issue by factoring an 80% reduction of WVCs within the fenced section as part of the net economic benefit analysis. Even after this reduction, our analysis still demonstrated that many fence lengths provided a net economic benefit. Additional technologies can be implemented at fence ends to help minimize animal intrusions to the right-of-way, such as rip-rap barriers for ungulates, electrical touch pads, animal-vehicle detection systems, speed reduction and lighting (Clevenger et al. 2002a, Huijser et al. 2007b). Local topographic features such as rock cuts, unsuitable habitat or waterways can be also tied into the fence design in order to reduce fence intrusions.

Another limitation of our study is that we used a fairly simple economic model: our figures do not include maintenance costs of the fence and are not adjusted for inflation even though we are using WVC records dating back to 1981. Thus, the cost figures we present here are useful for comparing the relative economic performance of fencing, but should not necessarily be interpreted as the true costs and benefits. Furthermore, the cost of WVC per species was derived from nation-wide values presented in Huijser et al. (2009). We have no reason to suspect that their values could not be applied to our study area, but some minor adjustments are likely needed. Likewise, the costs of mitigation are borne by the agencies that manage the road and wildlife, while the benefits are received by all of society. Indeed, a more complex economic evaluation is possible, but as far as we are aware, this is one of the first attempts to derive net economic benefits of highway mitigation measures (see Huijser et al. 2009).

The last caveat relates to how practitioners should apply our results to their own study area. WVCs in our study area are distributed fairly evenly along the highway when compared to nearby roads. Though Highway 93S bisects mountainous valleys, the valley bottom is wide and mostly level terrain. In other areas, such as narrow mountain valleys or along river courses, topography tends to channel animal movement (Clevenger et al. 2002c). Concentrated animal movements, in turn, increase the performance of smaller fence lengths. On the other hand, WVC distributions may be more dispersed in other areas than in KNP. In this case, fencing performance increases positively with the length of fencing, obviating some concern for fencing placement. We caution that our study results are based on a particular degree of spatial clustering found in our area and may not be directly applicable elsewhere.

Our analysis provides some insights on how effective mitigation 'could have' been had it been built in 1981. However, the landscape, wildlife and human components of our system are dynamic and past experiences may only approximate future ones. Roads, and many mitigation measures such as fencing and wildlife crossing structures, are largely static features on the landscape. Recognizing the disconnect between historical data and predicted future conditions requires an adaptive approach to managing WVCs. Highway mitigation that is constructed in phases or sections, along with a well planned study design that includes pre- and post-construction monitoring, creates a unique opportunity to apply the principles of adaptive management (Walters 1986, Roedenbeck et al. 2007). Lessons learned from previous experiences can then be applied to the planning and design of future highway mitigation phases (McGuire & Morall 2000). By having greater data available for decision-making, this 'adaptive mitigation' approach will reduce the amount of planning, cost and time required to achieve a desired level of performance in future mitigation projects.

Acknowledgements - we would like to thank Parks Canada staff for their assistance over the years collecting WVC data. We would also like to thank Lauren Oechsli and Benjamin Dorsey for their GIS support on this project. This project was funded by Parks Canada, the Western Transportation Institute at Montana State University, and the Woodcock, Wilburforce and Kendall Foundations.

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