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Cost–Benefit Analyses of Mitigation Measures Aimed at Reducing Collisions with Large Ungulates in the United States and Canada: a Decision Support Tool

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ABSTRACT. Wildlife–vehicle collisions, especially with deer (*Odocoileus* spp.), elk (*Cervus elaphus*), and moose (*Alces alces*) are numerous and have shown an increasing trend over the last several decades in the United States and Canada. We calculated the costs associated with the average deer–, elk–, and moose–vehicle collision, including vehicle repair costs, human injuries and fatalities, towing, accident attendance and investigation, monetary value to hunters of the animal killed in the collision, and cost of disposal of the animal carcass. In addition, we reviewed the effectiveness and costs of 13 mitigation measures considered effective in reducing collisions with large ungulates. We conducted cost–benefit analyses over a 75-year period using discount rates of 1%, 3%, and 7% to identify the threshold values (in 2007 U.S. dollars) above which individual mitigation measures start generating benefits in excess of costs. These threshold values were translated into the number of deer–, elk–, or moose–vehicle collisions that need to occur per kilometer per year for a mitigation measure to start generating economic benefits in excess of costs. In addition, we calculated the costs associated with large ungulate–vehicle collisions on 10 road sections throughout the United States and Canada and compared these to the threshold values. Finally, we conducted a more detailed cost analysis for one of these road sections to illustrate that even though the average costs for large ungulate–vehicle collisions per kilometer per year may not meet the thresholds of many of the mitigation measures, specific locations on a road section can still exceed thresholds. We believe the cost–benefit model presented in this paper can be a valuable decision support tool for determining mitigation measures to reduce ungulate–vehicle collisions.

Key Words: *animal–vehicle collisions; cost–benefit analysis; deer; economic; effectiveness; elk; human injuries and fatalities; mitigation measures; moose; roadkill; ungulate; vehicle repair cost; wildlife–vehicle collision*

INTRODUCTION

Wildlife–vehicle collisions affect human safety, property and wildlife. The total number of large mammal–vehicle collisions has been estimated at one to two million in the United States and at 45 000 in Canada annually (Conover et al. 1995, Tardif and Associates Inc. 2003, Huijser et al. 2007b). These numbers have increased even further over the last decade (Tardif and Associates Inc. 2003, Huijser et al. 2007b). In the United States, these collisions were estimated to cause 211 human fatalities, 29 000 human injuries and over one billion US dollars in property damage annually (Conover

et al. 1995). In most cases, the animals die immediately or shortly after the collision (Allen and McCullough 1976). In some cases, it is not just the individual animals that suffer. Road mortality may also affect some species on the population level (e. g., van der Zee et al. 1992, Huijser and Bergers 2000), and some species may even be faced with a serious reduction in population survival probability as a result of road mortality, habitat fragmentation, and other negative effects associated with roads and traffic (Proctor 2003, Huijser et al. 2007b). In addition, some species also represent a monetary value that is lost once an individual animal dies (Romin and Bissonette 1996, Conover 1997).

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Although this paper focuses on collisions with large ungulates, this group is not necessarily the most abundant or the most important species group hit by vehicles. Species groups most often reported in roadkill surveys include amphibians, reptiles, birds, and mammals (Seibert and Conover 1991, Holsbeek et al. 1999, Ament et al. 2008, Gryz and Krauze 2008). The relative proportion at which these species groups are recorded in roadkill surveys in different countries varies substantially: 1.8%–70.8% for amphibians, <0.1%–7.4% for reptiles, 3.1%–52% for birds, and 4.2%–87.2% for mammals (Seibert and Conover 1991, Kratky 1995, Holsbeek et al. 1999, Gryz and Krauze 2008, Hobday and Minstrell 2008). A review by Seiler (2003) showed that the numbers of road-killed birds and mammals in various countries are typically estimated at multiple millions per year. Surveys that include invertebrates indicate that mortality rates of invertebrates due to collision with vehicles are far higher than for vertebrates: in one study, 86% of all observations related to invertebrates (Seibert and Conover 1991). However, mitigation measures are most often implemented for species that are large enough to pose a threat to human safety or species whose population survival probability is severely affected by roads and traffic (e.g., Mansergh and Scotts 1989, van der Ree et al. 2009). In addition, data collected by law enforcement agencies (crash data) and transportation agencies (carcass data) are typically limited to large mammals (Huijser et al. 2007a).

Over 40 types of mitigation measures aimed at reducing collisions with large ungulates have been described (see reviews in Hedlund et al. 2004, Knapp et al. 2004, Huijser et al. 2007b). Examples include warning signs that alert drivers to potential animal crossings, wildlife warning reflectors or mirrors (e.g., Reeve and Anderson 1993, Ujvári et al. 1998), wildlife fences (Clevenger et al. 2001), and animal detection systems (Huijser et al. 2006b). However, the effectiveness and costs of these mitigation measures vary greatly. When the effectiveness is evaluated in relation to the costs for the mitigation measure, important insight is obtained regarding which mitigation measures may be preferred, at least from a monetary perspective. Nonetheless, very few cost–benefit analyses exist (but see, e.g., Reed et al. 1982), and although this may seem surprising, wildlife–vehicle collisions, at least until recently, are not always included in safety analyses by transportation agencies, let alone in cost–benefit analyses (Knapp and Witte 2006).

Transportation agencies in the United States and Canada typically do not have access to basic cost and benefit data, and do not have comprehensive analysis tools available to them (Knapp and Witte 2006). Over the last decades, the dominant practice for transportation agencies has been to install wildlife warning signs when (variable) thresholds were reached for ungulate–vehicle collisions (Knapp and Witte 2006). However, the implementation of these signs has typically not been based on a cost–benefit analysis. In addition, such thresholds typically relate to relatively short road sections (e.g., 0.25 or 0.50 miles (402 m or 805 m)), whereas ungulate–vehicle collisions typically need to be analyzed and mitigated at a larger spatial scale. Finally, anecdotal information and crash and carcass data summaries are also used to justify more substantial mitigation measures such as wildlife fencing combined with safe wildlife crossing opportunities, but decisions to implement such mitigation measures are rarely based on cost–benefit analyses (Knapp and Witte 2006; Pat Basting, Montana Department of Transportation, pers. comm.; Doug Herbrand, Ontario Ministry of Transportation, pers. comm.).

In this paper, we compare the monetary costs and benefits of a range of mitigation measures aimed at reducing collisions with large ungulates. In the United States, most of the wildlife–vehicle collisions reported by agencies involve deer (*Odocoileus* spp.). In addition, the vast majority of all animal–vehicle collisions that result in human injury (86.9%) or human fatality (77%) involve deer as well (Conn et al. 2004, Williams and Wells 2005). The numbers vary between regions: in California, deer amount to 54.4% of the reported animal–vehicle collisions, in Maine 81.2% (Huijser et al. 2007b). In certain areas, e.g., Maine, collisions with moose (*Alces alces*) are relatively numerous (15.1%) (Huijser et al. 2007b). Of all the claims submitted to a major auto insurance company in the United States (national market share about 17.5%) in 2006–2007 for vehicle repair as a result of a collision with deer, elk (*Cervus elaphus*), or moose, 99.2% related to deer, 0.5% to elk, and 0.3% to moose (n is approximately 180 000) (Dick Luedke, State Farm Insurance, pers. comm.). In British Columbia, Canada, 85.6% of all reported animals killed by traffic were deer (78.6%) or moose (7.0%) (Sielecki 2004). In the Ottawa-Carleton area, Canada, 93.1% of all reported animal–vehicle collisions involved deer (92.2%) or moose (0.9%) (Tardif and Associates Inc. 2003). For this paper,

we conducted separate analyses for the costs and benefits of mitigation measures aimed at reducing collisions with deer (white-tailed deer (*O. virginianus*) and mule deer (*O. hemionus*) combined), elk, and moose.

Our cost–benefit analyses do not include passive-use costs. Passive or nonuse values are generally based on existence or bequest motives and include values in addition to those that arise directly due to the collision (Krutilla 1967, Daily et al. 1997). In this context, passive values could include the value individuals (even those who perhaps never drive the road section of interest) place on having viable populations of certain species and well-functioning ecosystems as a result of the reduced road mortality and a certain amount of connectivity for wildlife associated with a mitigation measure. Connectivity across roads for wildlife is also in the interest of human safety as animals are more likely to break through a barrier (e.g., wildlife fencing) if safe crossing opportunities are not provided or if they are too few, too small, or too far apart. Even if wildlife fencing is combined with safe crossing opportunities for wildlife, animals may still end up in between the fences, caught in the transportation corridor, and these animals pose a risk to human safety. For these reasons, it is considered good practice to accompany absolute barriers, such as wildlife fencing, with safe crossing opportunities for wildlife and escape opportunities for animals that end up in between the fences. For this paper, we addressed the importance of safe crossing opportunities for wildlife by reviewing the individual mitigation measures for their potential barrier effect on the movements of large ungulates.

The results of our economic analyses apply to the United States and Canada, but not necessarily to other countries or regions, because we used species characteristics and economic data from these two countries. Furthermore, we realize that the results of the analyses are directly dependent on the parameters included in the analyses and the assumptions and estimates required to conduct the analyses. Nonetheless, the results of the cost–benefit analyses allow for much needed direction for transportation agencies and natural resource management agencies in the implementation and further research and development of mitigation measures aimed at reducing collisions with large ungulates.

METHODS

Cost–Benefit Analyses

We estimated the effectiveness of 13 types of mitigation measures for reducing collisions with large ungulates such as deer, elk, and moose, and whether these mitigation measures still allow animals to cross the road (Table 1). Of the 13 measures listed, only wildlife fencing is an absolute barrier for large ungulates. In addition, we estimated the costs (in 2007 US\$) of these mitigation measures per year over a 75-year period (Appendix 1, Table 1). The costs included design, construction or implementation, maintenance, and removal efforts. The 75-year period is equal to the longest lifespan of the mitigation measures reviewed (i.e., underpasses and overpasses). In the 75th year, no new investments were projected (only maintenance and removal costs) for the following mitigation measures: wildlife fence alone (Fig. 1); wildlife fence, gap, and crosswalk; wildlife fence, underpasses, and jump-outs (Figs. 2 and 3); wildlife fence, and under- and overpasses (Fig. 4); wildlife fence and animal detection systems (Fig. 5); elevated roadway; and road tunnel. Jump-outs are earthen ramps that allow animals that are trapped in between the fences in the road corridor to walk up to the top of the fence and jump down to safety. Well designed jump-outs are low enough to allow animals to jump to safety, and high enough to discourage them from jumping up into the road corridor.

We also estimated the benefits generated by the 13 mitigation measures. The benefits are a combination of the effectiveness of the mitigation measures in reducing collisions with large ungulates and the costs associated with the average collision. The cost of a collision with a large ungulate typically increases with the size and weight of the species. For this analysis, we estimated the costs for the average collision with a deer, an elk, or a moose (Appendix 2, Table 2). Some mitigation measures take considerable planning and installation time. For such measures, we did not project any benefits in the first year of the cost–benefit analyses. This delay in the start of the benefits applied to all mitigation measures, except seasonal signs, vegetation removal, population culling, relocation, and anti-fertility treatment.

For our cost–benefit analyses, all costs and benefits are in real terms (i.e., constant 2007 US\$).

Table 1. The estimated effectiveness, present value costs (in 2007 US\$, 3% discount rate), and costs per percent reduction of mitigation measures aimed at reducing collisions with large ungulates over a 75-year time period. The measures are ordered based on their estimated effectiveness. If a measure is estimated to be 86% effective, it means that ungulate–vehicle collisions are estimated to reduce by 86% as a result of the implementation of that mitigation measure (e.g., a reduction from 100 collisions to 14 collisions).

Mitigation measure	Effectiveness	Crossing opportunity?	Source	Present value costs (US\$)	Costs per percent reduction (US\$)
Seasonal wildlife warning sign	26%	Yes	Sullivan et al. (2004): 51%; Rogers (2004): 0%	\$3728	\$143
Vegetation removal	38%	Yes	Jaren et al. (1991): 56%; Lavsund and Sandegren (1991): 20%	\$16 272	\$428
Fence, gap, crosswalk	40%	Yes	Lehnert and Bissonette (1997): 42%, 37%	\$300 468	\$7512
Population culling	50%	Yes	Review in Huijser et al. (2007a)	\$94 809	\$1896
Relocation	50%	Yes	Review in Huijser et al. (2007a)	\$391 870	\$7837
Anti-fertility treatment	50%	Yes	Review in Huijser et al. (2007a)	\$2 183 207	\$43 664
Fence (incl. dig barrier)	86%	No	Reed et al. (1982) 79%; Ward (1982): 90% Woods (1990): 94%–97%; Clevenger et al. (2001): 80%; Dodd et al. (2007): 87%	\$187 246	\$2177
Fence, underpass, jump-out	86%	Yes	Reed et al. (1982) 79%; Ward (1982): 90% Woods (1990): 94%–97%; Clevenger et al. (2001): 80%; Dodd et al. (2007): 87%	\$538 273	\$6259
Fence, under- and overpass, jump-out	86%	Yes	Reed et al. (1982) 79%; Ward (1982): 90% Woods (1990): 94%–97%; Clevenger et al. (2001): 80%; Dodd et al. (2007): 87%	\$719 667	\$8368
Animal detection system (ADS)	87%	Yes	Mosler-Berger and Romer (2003): 82%; Dodd and Gagnon (2008): 91%	\$1 099 370	\$12 636
Fence, gap, ADS	87%	Yes	Mosler-Berger and Romer (2003): 82%; Dodd and Gagnon (2008): 91%	\$836 113	\$9610
Elevated roadway	100%	Yes	Review in Huijser et al. (2007a)	\$92 355 498	\$923 555
Road tunnel	100%	Yes	Review in Huijser et al. (2007a)	\$147 954 696	\$1 479 547

Accordingly, as we excluded inflation effects in our benefit and cost streams over time, we also used real (as opposed to nominal) discount rates. Presenting the analysis in nominal terms with inflation included in future values and an inflation component in the discount term would be mathematically equivalent. In order to correctly compare benefit and cost elements, which are distributed asymmetrically

over time, we computed present discounted values and amortized these into equivalent annual terms. The typical pattern for the mitigation measures we examined is that costs are largely construction oriented in the present (e.g., an investment in a fence with an underpass in the first year of a 75-year period) whereas benefits are distributed more uniformly over the life of the project (i.e., a certain

Fig. 1. A 2.4 m (8 ft) high large-mammal fence, with smaller mesh sizes toward the bottom, on U.S. Highway 93 on the Flathead Reservation, Montana, USA (copyright: Marcel Huijser).



reduction in collisions and associated costs each year). In this situation, the cost–benefit analysis is sensitive to the discount rate chosen. The discount rate simply corrects for the time value of money. For example, if an individual can earn a fixed 3% interest on savings or investments, then a dollar today is worth US\$1.03 one year from now. Conversely, a dollar promised to be paid one year from now is worth only (discounted to) about US\$0.97 today.

Following the guidance provided in the U.S. Office of Management and Budget (OMB) Circular A-94

(U.S. OMB 1992) and other federal guidelines (U.S. Environmental Protection Agency 2000), we conducted the analyses for real discount rates of 7%, 3%, and 1%. The 7% rate is required by OMB for federal benefit–cost analyses and is based on a shadow price of capital theory; specifically (at least in 1992) 7% is OMB’s estimate of the real after-tax return on investment in the private sector (essentially the opportunity cost of instead investing in public projects). A more widely accepted discount parameter for at least intra-generational accounting is choosing a social discount rate based on the rate at which individuals translate

Fig. 2. A large-mammal underpass (7–8 m (23–26.2 ft) wide, 4–5 m (13.1–16.4 ft) high) along U.S. Highway 93 on the Flathead Reservation, Montana, USA (copyright: Marcel Huijser).



consumption through time with reasonable certainty (e.g., a consumption rate of interest theory). For this, historical returns on safe assets such as U.S. Treasury securities are used (post-tax and corrected for inflation), with empirical estimates for rates in the 1% to 3% range (U.S. Environmental Protection Agency 2000). For inter-generational discounting (for which a project with a lifespan of 75 years would obviously qualify) other theories based in part on ethical considerations that explicitly trade-off the well-being of current and future generations come into play, and rates of 0.5% to 3% are plausible. As an example from the economics literature, a recent

survey of several thousand economists on the issue of an appropriate discount rate for the problem of global warming indicated a wide-range of opinions on the appropriate rate, rates declining over the time period of the analysis from about 4% to 0% for the very long term, and a long-term average rate of 1.75% in real terms (Weitzman 2001). Sumaila and Walters (2005) provide an alternative framework for intergenerational discounting and an overview of the recent literature on this issue.

After estimating the costs for each mitigation measure, and after correcting for the discount rate,

Fig. 3. A short section of perpendicular fence to guide animals on top of a jump-out along a 2.4 m (8 ft) high fence along U.S. Highway 93 on the Flathead Reservation, Montana, USA (copyright: Marcel Huijser).



we calculated how much benefit (in 2007 US\$) each mitigation measure needs to generate over a 75-year period in order to break even and have the benefits exceed the costs (threshold values). Equation 1 shows our methods for estimating costs:

$$A_j = \left[\sum_{t=1}^n \frac{c_{tj}}{(1+d)^t} \right] \left[\frac{(1+d)^n \cdot d}{(1+d)^n - 1} \right] \quad (1)$$

The first term is simply the present value of costs over the period t equals 1 to n with discount rate d and annual costs (c_{tj}) in year t for mitigation measure j . The second term is an amortization factor (the share that yields the annual equivalent of a fixed

Fig. 4. Wildlife overpass in Banff National Park, Alberta, Canada (copyright: Marcel Huijser).



sum over some time period, as in the annual payments on a 30-year mortgage); the product of the two terms equals A_j , which is the amortized real annual cost over period n for technology j . Annual benefits are given by Eq. 2:

$$B_j = r_j k \sum_{i=1}^m \alpha_i c_i + \sum_{i=1}^m v_{ij} \quad (2)$$

Annual benefits are the sum of the reduction in direct collision costs for species i (equals 1 to m) and any annual nonuse or passive-use values v_{ij} for these species. With respect to direct collision costs, r_j is

the reduction in wildlife–vehicle collisions from mitigation measure j (r is a ratio) and k is the initial pre-mitigation level of wildlife–vehicle collisions per kilometer per year for the road section of interest. The term rk accordingly is the reduction in the number of wildlife–vehicle collisions. The average species-weighted average cost per collision is the summation of the share of collisions (α_i) due to species i times species-specific collision costs c_i . The summed product of the reduction in collisions and the average cost per collision ($\alpha_i c_i$) gives the benefits associated with a given mitigation measure. Setting annual benefits for mitigation measure j equal to annual costs and solving for k yields the breakeven level of pre-mitigation collisions, which we designate k_j^* , above which annual benefits will exceed costs, e.g., net benefits are positive, as shown in Eq. 3:

Fig. 5. Animal detection system along U.S. Highway 191 in Yellowstone National Park, Montana, USA (copyright: Marcel Huijser).



Table 2. Summary of estimated costs (in 2007 US\$) for the average deer-, elk-, and moose-vehicle collision.

Description	Deer (US\$)	Elk (US\$)	Moose (US\$)
Vehicle repair costs per collision	\$2622	\$4550	\$5600
Human injuries per collision	\$2702	\$5403	\$10 807
Human fatalities per collision	\$1002	\$6683	\$13 366
Towing, accident attendance, and investigation	\$125	\$375	\$500
Hunting value animal per collision	\$116	\$397	\$387
Carcass removal and disposal per collision	\$50	\$75	\$100
Total	\$6617	\$17 483	\$30 760

$$k_j^* = \frac{A_j - \sum v_{ij}}{(r_j \cdot \sum \alpha_i \cdot c_i)} \quad (3)$$

As one would expect, the number of collisions required is directly proportional to the mitigation measure cost A (the higher the costs, the more collisions needed to justify) and inversely proportional to the benefit (reduction in collisions) achieved by the mitigation measure. To the extent there are annual passive-use benefits (v_{ij}), these reduce annual costs. For the simplified case of a single species and no passive-use values, the breakeven value is simply (Eq. 4):

$$k_j^* = \frac{A_j}{r_j \cdot c_i} \quad (4)$$

Note that the right-hand term is simply total annual costs of the mitigation measure divided by the benefits (avoided costs) per collision. If one

expresses r_j in terms of percent reduction, then A_j/r_j is the cost of a 1% reduction in collisions. It is useful to compute this unit cost (cost per 1% reduction) in the following section in comparing the costs of different mitigation measures. The next two sections provide a summary of the effectiveness and costs of the mitigation measures, and the costs associated with deer-, elk-, and moose-vehicle collisions.

Effectiveness and Costs of Mitigation Measures

We reviewed approximately 40 different types of mitigation measures or combinations of mitigation measures that aim to reduce collisions with large animals (deer and larger) (for full review see Huijser et al. 2007b). Based on the available data, 13 of these measures were considered effective in reducing collisions with large animals (effectiveness >0%) (Table 1). For example, if there were 10 reported collisions with large ungulates per kilometer per year on a road section, then the implementation of a combination of wildlife fencing, underpasses, and jump-outs is estimated to reduce these collisions by 86% to 1.4 reported collisions per kilometer per year (Table 1). If more than one estimate was available for the effectiveness of each of the 13 mitigation measures reviewed, the mean was calculated. As the

effectiveness of some of the mitigation measures is highly variable or based on only one study, additional studies may lead to an adjustment of these values at a later time. Mitigation measures considered ineffective (effectiveness estimated at 0% (Huijser et al. 2007b)), lacking effectiveness data, or having insufficient data were excluded from the cost–benefit analyses in this paper.

Each mitigation measure's suitability depends on the species concerned, the specific objectives of a project, and local circumstances. This paper does not discuss the advantages and disadvantages of each mitigation measure, but it is important to be aware that some mitigation measures may only be suited for very specific circumstances. For example, population culling, the relocation of individuals or infertility treatment of individuals may only be practical and effective for relatively small and closed populations (Seagle and Close 1996, Rudolph et al. 2000). Furthermore, such measures are typically applied to deer rather than other species. See Huijser et al. (2007a) for a discussion on other considerations.

The estimated costs for each of the mitigation measures over a 75-year period vary greatly, as did the costs per percent reduction in collisions (Table 1). Appendix 1 provides a rationale for the estimated costs of the individual mitigation measures.

Cost Estimates for Deer-, Elk-, and Moose–Vehicle Collisions

The justification for the cost estimates for deer-, elk-, and moose–vehicle collisions is in Appendix 2. The total estimated costs for the average deer-, elk-, and moose–vehicle collision is summarized in Table 2. As we calculated the costs for an average collision, the costs of collisions that result in human injuries or fatalities, in addition to property damage, are higher than this average. Similarly, the costs of collisions that result in property damage only are lower than these average costs. The advantage of using the costs of an average collision is that no assumptions have to be made whether a particular accident (past or future) did or will result in human injuries or fatalities; this is averaged out. Most of the costs are associated with human injuries and fatalities (deer: 56.0%; elk: 69.1%; moose: 78.6%) rather than vehicle repair costs (deer: 39.6%; elk: 26.0%; moose: 18.2%). Based on a total estimate of one to two million collisions with large mammals

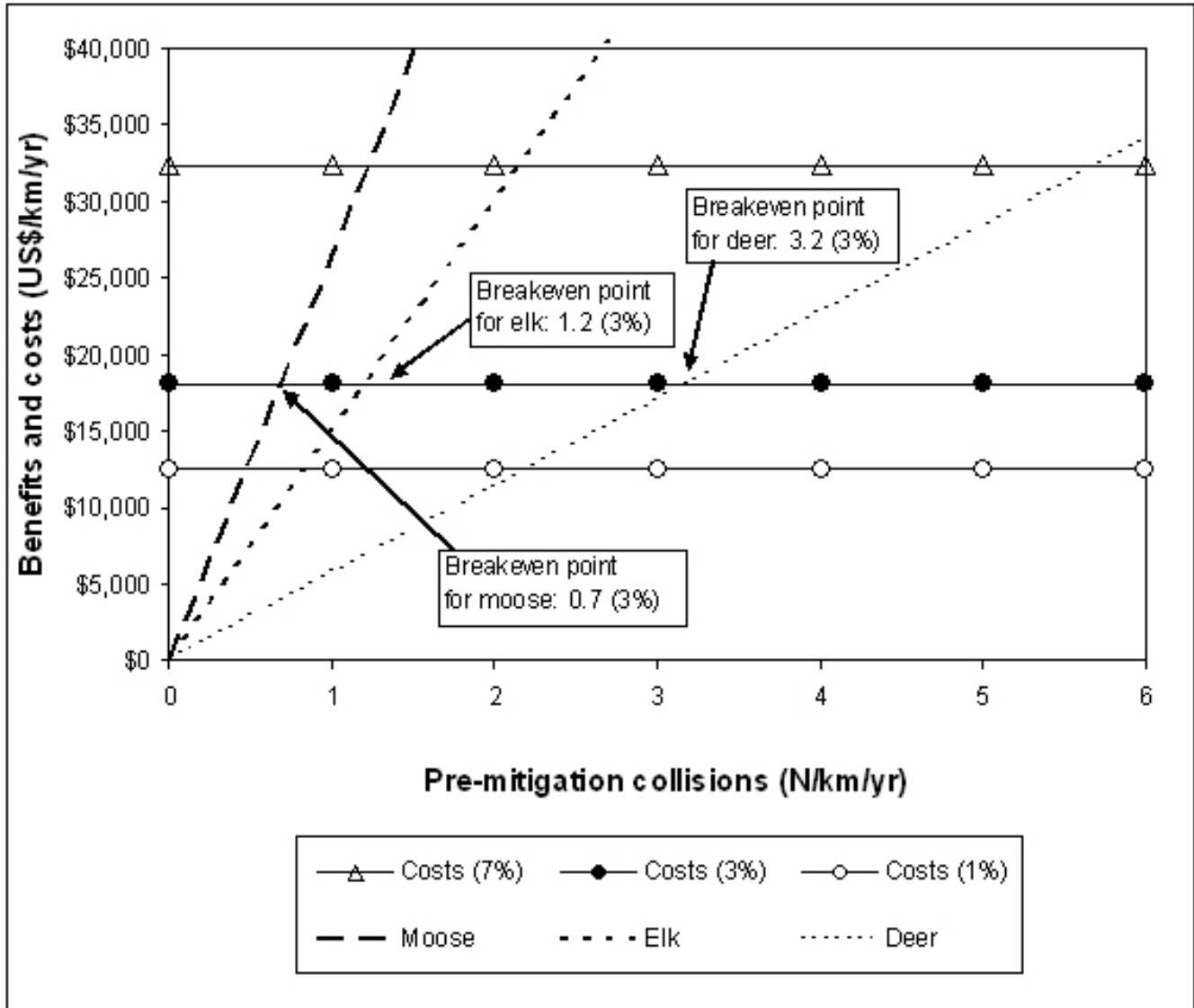
per year in the United States (Huijser et al. 2007b) and the estimate that 99.2% of all reported wildlife–vehicle collisions related to deer, 0.5% to elk, and 0.3% to moose (see introduction), the total estimated annual costs associated with ungulate–vehicle collisions is estimated at US\$6 247 759 000–US\$12 495 518 000. In Canada, with an estimated 45 000 large mammal–vehicle collisions, the estimated annual costs are US\$281 149 155 (Tardif and Associates Inc. 2003). Although we acknowledge that there is geographical variation in the body size of deer, elk, and moose, and thus in the costs associated with a collision, the estimates presented in this manuscript are typically based on average values for large geographical areas (e.g., a nation) or the results of several studies in different geographical areas, resulting in estimates for the United States and Canada combined rather than estimates for a particular region.

RESULTS

Illustration Output Cost–Benefit Model

Figure 6 shows the threshold values (in 2007 US\$) for a specific mitigation measure: fencing with underpasses and jump-outs. For this specific mitigation measure, there is an initial construction cost in the first year of US\$416 191, with annual maintenance of US\$1500 per year and fence removal and replacement in year 25 and 50 of US\$107 500 and removal less salvage in year 75 of US\$26 500 (all costs in 2007 US\$ per kilometer) (see Appendix 1 for justification). The present value (3% discount rate) of this mitigation measure is US\$538 273 and annual amortized value per kilometer is US\$18 123. The annual amortized values at 7% and 1% are US\$32 457 and US\$12 437, respectively. These annual costs at the three discount rates are shown as horizontal lines (Fig. 6). The lines representing the costs associated with pre-mitigation collisions with deer, elk, and moose cross the horizontal lines representing the annual amortized values at the break-even points. For 3% discount rate, the break-even point for deer, elk, and moose is 3.2, 1.2, and 0.7 collisions per kilometer per year, respectively (Fig. 6). If more collisions occur, then implementing fencing with underpasses and jump-outs generates economic benefits in excess of costs. Similarly, if fewer collisions occur then the implementation of this mitigation measure has costs in excess of benefits.

Fig. 6. The number of deer-, elk-, and moose-vehicle collisions per kilometer per year (dotted lines) needed to reach the threshold values (7%, 3%, and 1% discount rate) (in real 2007 US\$) (solid lines) for fencing with underpasses.



Another way to look at the same data is in terms of the actual “product” or output of the mitigation measures, which is the number of collisions avoided per kilometer per year (Fig. 7). From this perspective, the average benefits per collision avoided are constant (horizontal lines in Fig. 7) and depend on the species: deer US\$6617, elk US\$17 483, and moose US\$30 760 per kilometer per year.

Average costs per collision avoided, however, decline with the number of collisions avoided, illustrating the spreading of fixed costs that underlies the economics of these mitigation measures. The break-even point for deer, elk, and moose is at 2.7, 1.0, and 0.6 collisions avoided per kilometer per year, respectively (Fig. 7). If more collisions are avoided, then fencing with

underpasses and jump-outs generates economic benefits in excess of costs. Similarly, if fewer collisions are avoided then this mitigation measure has costs in excess of benefits. Note that the break-even values divided by the reduction achieved by the specific fencing with underpasses mitigation measure of 0.86 (or 86%) yields the break-even point in terms of pre-mitigation collisions (Fig. 6).

Threshold Values for the Mitigation Measures

The minimum amount (in 2007 US\$) that a mitigation measure needs to generate in order to reach the break-even point increases with the discount rate (Tables 3 and 4). However, this value is not dependent on the discount rate for mitigation measures that require the same investment every year (i.e., for vegetation removal and anti-fertility treatment) (Table 3). These dollar-value thresholds were translated into break-even points for deer-, elk-, and moose-vehicle collisions per kilometer per year (Tables 3 and 4). If a road section has costs or wildlife-vehicle collision numbers that exceed these threshold values, then the benefits of that mitigation measure exceed the costs over a 75-year time period (measured in 2007 US\$). For example, if a road section averages 0.1 deer-vehicle collisions per kilometer per year, and if the collisions are concentrated in certain times of the year, a seasonal warning sign would be economically feasible (because the threshold value of <0.1 (3% discount rate) is exceeded), but this measure is only estimated to reduce collisions by 26% (see Table 1). If a road section averages 4.4 deer-vehicle collisions per kilometer per year, a combination of wildlife fencing, under- and overpasses, and jump-outs would be economically feasible (because the threshold value of 4.3 (3% discount rate) is exceeded), and this measure is estimated to reduce collisions by 86% (see Table 1). Naturally, other mitigation measures that have threshold values lower than 4.4 deer per kilometer per year would also be economically feasible. Note that the threshold values presented in Tables 3 and 4 are based on a series of assumptions and estimates and that they should be taken as indicative values rather than exact values.

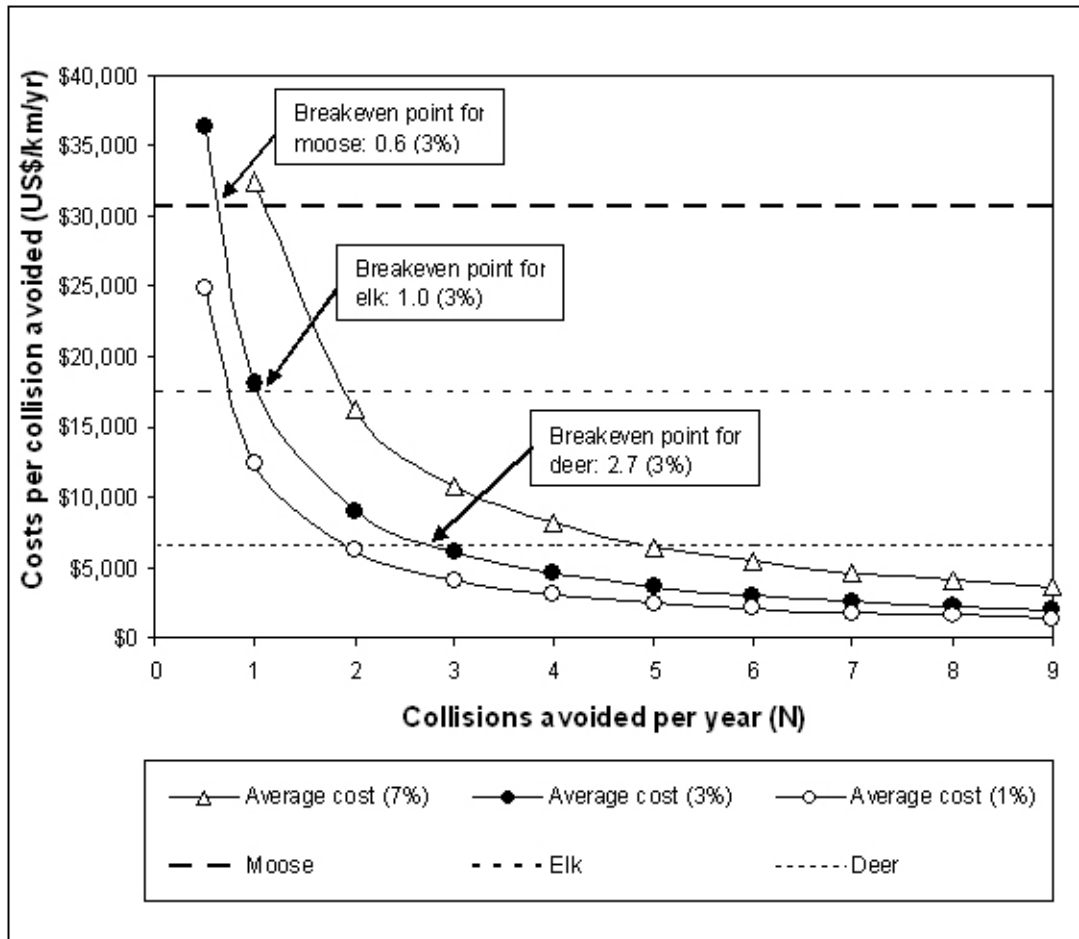
Real-World Examples

The costs associated with deer-, elk-, and moose-vehicle collisions for 10 road sections in the United States and Canada varied between US\$3636 and US\$46 155 per kilometer per year (Table 5). Even though some of the road sections only have data for a relatively short period, and the search and reporting effort varies for the different road sections, the average costs are higher than the threshold values for some of the mitigation measures (see Tables 3 and 4), indicating that the benefits of implementing such mitigation measures over the full length of the road sections concerned exceed the costs, and that these measures would be economically feasible. When comparing the costs per kilometer per year to the threshold values in Tables 3 and 4, please note that these threshold values are based on a divided four-lane road, and that two-lane roads have lower threshold values for some of the mitigation measures (e.g., those that include under- or overpasses). A more detailed cost analysis for one of the road sections in Table 5, MT Hwy 83, showed that, even though the average costs per kilometer per year may not meet the thresholds of many of the mitigation measures, certain locations on a road section can still exceed these thresholds (Fig. 8). For example, the benefits of animal detection systems as a stand-alone mitigation measure exceed the costs on 4.2% of the 76.9 km (47.8 miles) road section. Similarly, this percentage is 9.4% for wildlife fencing with gaps and animal detection systems in these gaps and jump-outs: 16.3% for wildlife fencing with under- and overpasses and jump-outs; and 26.8% for wildlife fencing with underpasses and jump-outs (Fig. 8).

DISCUSSION

The costs associated with deer-, elk-, and moose-vehicle collisions are substantial. Most of the costs are associated with human injuries and fatalities (deer 56.0%; elk 69.1%; moose: 78.6%) rather than vehicle repair costs (deer: 39.6%; elk: 26.0%; moose: 18.2%). Of the approximately 40 different types of mitigation measures reviewed, only 13 were considered to be effective in reducing collisions with large ungulates. However, the degree of effectiveness and the costs of these 13 mitigation measures vary greatly and, consequently, there are substantial differences in the threshold values

Fig. 7. The average costs per collision avoided per year for deer, elk, and moose for the mitigation measure fencing with underpasses (solid lines) (at 7%, 3%, and 1% discount rate) and the costs associated with the average deer-, elk-, or moose-vehicle collision (dotted lines) (all in real 2007 US\$).



between the individual mitigation measures above which the benefits of a mitigation measure exceed the costs. Collision and carcass data from 10 road sections throughout the United States and Canada showed that some road sections easily meet the threshold values for some of the mitigation measures. This means that the benefits of implementing such mitigation measures over the full length of the road sections concerned exceed the costs and that the implementation of mitigation measures would be economically feasible. However, when calculating the average costs of wildlife-vehicle collisions over relatively long road sections, potential concentrations of wildlife-

vehicle collisions are ignored. Therefore, it is important that more detailed analyses are carried out at a finer spatial scale (e.g., at 0.1–1.0 km or 0.1–1.0 mile resolution) to identify road sections where the benefits of mitigation measures may exceed the costs. Previous cost-benefit analyses estimated that wildlife fencing and wildlife fencing in combination with underpasses required 7.5 and 11.3 deer-vehicle collisions per kilometer per year, respectively, at a discount rate of 6% (Reed et al. 1982). These thresholds are higher than in our study, primarily because Reed et al. (1982) did not include the costs associated with human injuries and fatalities.

Table 3. Threshold values for individual mitigation measures that are estimated to reduce collisions with large ungulates by $\leq 50\%$ (see Table 1 for estimated percentages).

Threshold values	Disco- unt rate	Seasonal sign	Vegetation removal	Fence, gap, signs, crosswalk, jump-outs	Population culling	Relocation	Anti-fertility treatment
US\$/km/yr	1%	\$114	\$530	\$8153	\$3040	\$12 652	\$71 110
US\$/km/yr	3%	\$121	\$530	\$10 116	\$3099	\$12 764	\$71 110
US\$/km/yr	7%	\$140	\$530	\$14 972	\$3215	\$13 164	\$71 110
deer/km/yr	1%	<0.1	0.2	3.1	0.9	3.8	21.5
deer/km/yr	3%	<0.1	0.2	3.8	0.9	3.9	21.5
deer/km/yr	7%	<0.1	0.2	5.7	1.0	4.0	21.5
elk/km/yr	1%	<0.1	<0.1	1.2	0.4	1.5	8.1
elk/km/yr	3%	<0.1	<0.1	1.5	0.4	1.5	8.1
elk/km/yr	7%	<0.1	<0.1	2.1	0.4	1.5	8.1
moose/km/yr	1%	<0.1	<0.1	0.7	0.2	0.8	4.6
moose/km/yr	3%	<0.1	<0.1	0.8	0.2	0.8	4.6
moose/km/yr	7%	<0.1	<0.1	1.2	0.2	0.9	4.6

Although it may appear attractive to implement mitigation measures that have relatively low threshold values, not all mitigation measures reduce wildlife–vehicle collisions substantially. Therefore, whereas mitigation measures with relatively low threshold values and with limited effectiveness may be considered for road sections with relatively few wildlife–vehicle collisions, mitigation measures with higher threshold values and higher effectiveness may be considered for road sections that have relatively many wildlife–vehicle collisions.

Wildlife fencing as a stand-alone mitigation measure has relatively low threshold values and reduces wildlife–vehicle collisions substantially. However, we strongly advise against increasing the

barrier effect of roads and traffic without providing for safe crossing opportunities at appropriate intervals (see, e.g., Bissonette and Adair 2008, Huijser et al. 2008). The reason wildlife fencing has relatively low thresholds is that connectivity for wildlife (a passive-use cost) was not included in our cost–benefit analyses. However, depending on the species and local population structure, connectivity across the landscape, including roads, can be critical for the long-term population viability of the species concerned, and perhaps especially for species that may not be frequently hit by cars and that have low population density in the area (e.g., Jaeger and Fahrig 2004). Future cost–benefit analyses may include a monetary value for having viable populations of different species, as well as other passive-use values.

Table 4. Threshold values for individual mitigation measures that are estimated to reduce collisions with large ungulates by $\geq 80\%$ (see Table 1 for estimated percentages).

Threshold values	Discount rate	Fence	Fence, underpass, jump-outs	Fence, under- and overpass, jump-outs	ADS	Fence, gap, ADS, jump-outs	Elevated roadway	Road tunnel
US\$/km/yr	1%	\$5223	\$12 437	\$15 975	\$35 279	\$25 634	\$2 233 094	\$3 328 567
US\$/km/yr	3%	\$6304	\$18 123	\$24 230	\$37 014	\$28 150	\$3 109 422	\$4 981 333
US\$/km/yr	7%	\$8931	\$32 457	\$45 142	\$41 526	\$34 437	\$5 369 961	\$9 246 617
deer/km/yr	1%	0.9	2.2	2.8	6.1	4.5	337.5	503.0
deer/km/yr	3%	1.1	3.2	4.3	6.4	4.9	470.0	752.8
deer/km/yr	7%	1.6	5.7	7.9	7.2	6.0	811.6	1397.4
elk/km/yr	1%	0.4	0.8	1.1	2.3	1.7	127.7	190.4
elk/km/yr	3%	0.4	1.2	1.6	2.4	1.9	177.9	284.9
elk/km/yr	7%	0.6	2.2	3.0	2.7	2.3	307.2	528.9
moose/km/yr	1%	0.2	0.5	0.6	1.3	1.0	72.6	108.2
moose/km/yr	3%	0.2	0.7	0.9	1.4	1.1	101.1	161.9
moose/km/yr	7%	0.3	1.2	1.7	1.6	1.3	174.6	300.6

Wildlife fencing in combination with underpasses and jump-outs, or a combination of under- and overpasses and jump-outs, have thresholds low enough to be met at many road sections that have a concentration of collisions with large ungulates. Although the costs for an individual wildlife overpass is typically many times that for a wildlife underpass (estimated at 10 times higher costs, see Appendix 1), wildlife overpasses only increase the threshold values by 28.4%, 33.7% or 39.1% (at 1%, 3%, or 7% discount rate, respectively) when used sparingly in large-scale mitigation projects (in this case once every 24 km, see Appendix 1).

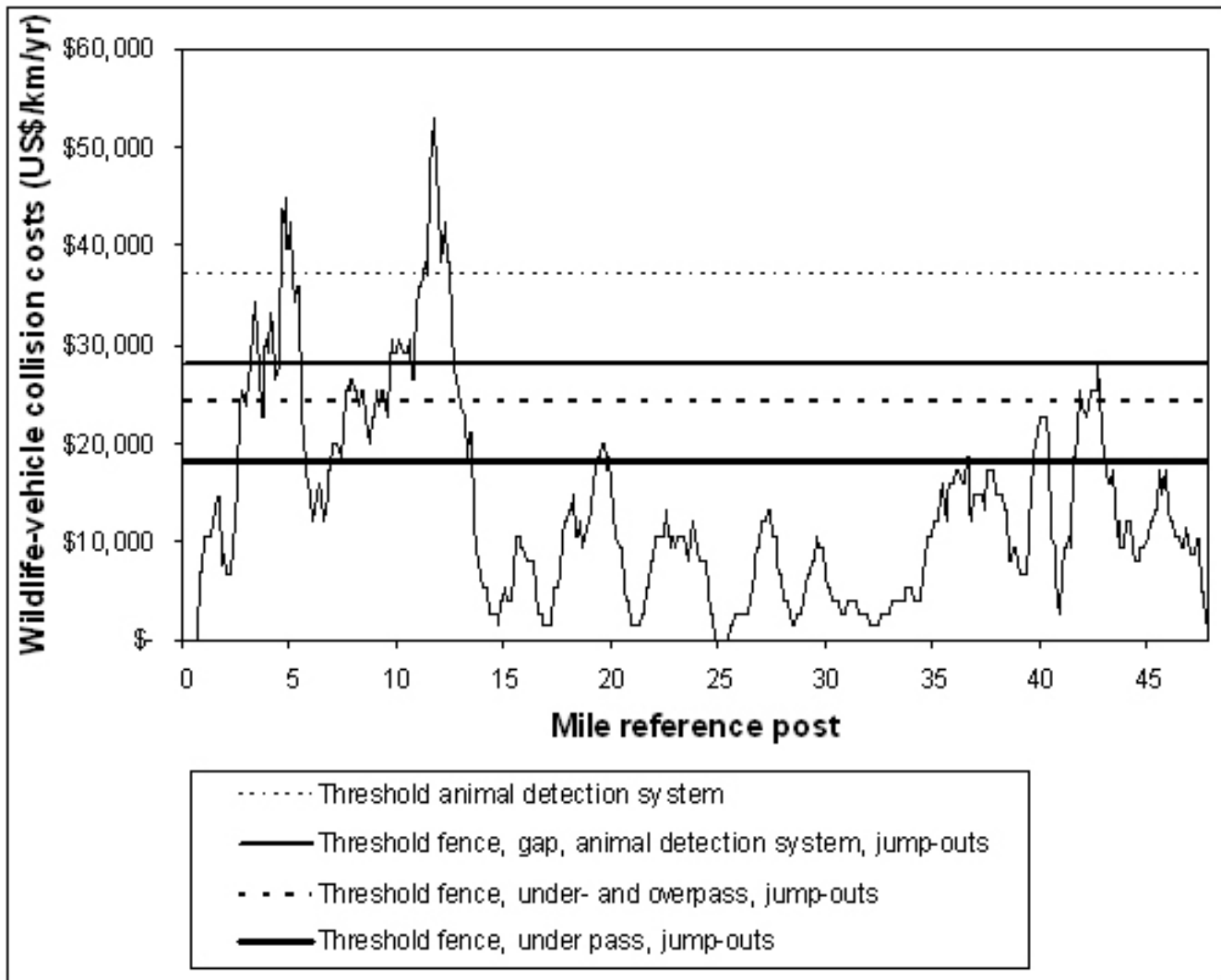
Animal detection systems as a stand-alone mitigation measure, and wildlife fencing combined with both jump-outs and animal detection systems

installed at gaps, have higher thresholds than wildlife fencing in combination with under- and overpasses and jump-outs, but they still are low enough to be met at many road sections that have a concentration of collisions with large ungulates. Nonetheless, although the data on the effectiveness of animal detection systems are encouraging, the estimate of the effectiveness of this mitigation measure are not nearly as robust as that for wildlife fencing in combination with under- and overpasses. Therefore, animal detection systems should still be considered experimental (see Huijser et al. (2006a) for a discussion on the relative strengths and weaknesses of animal detection systems and wildlife fencing in combination with under- and overpasses).

Table 5. The cost of deer-, elk-, and moose-vehicle collisions for selected road sections in the USA and Canada (all in 2007 US\$). R = research project, HM = highway maintenance reports, AR = highway accident reports, PWI = park warden incident reports, MSR = meat salvage reports.

Road section	Road length (km)	Data collection and year	Collisions/km/yr (costs in 2007 US\$)	Total cost/km/yr (US\$)	Source
SR260 (Christopher Creek section), Payson, AZ, USA	7.2	R, HM, AR (2002–2003)	2.64 elk (\$46 155)	\$46 155	Dodd et al. 2007
I-90 (309.0–330.9) (four-lane), Bozeman Pass, MT, USA	35.2	R, HM (2003)	3.38 deer (\$22 365) 0.21 elk (\$3671) 0.06 moose (\$1845)	\$27 881	Hardy et al. 2006
I-80/90 (50.0–70.0), Indiana Toll Road (four-lane), IN, USA	32.2	HM (2005)	2.89 deer (\$19 123)	\$19 123	Sedat Gulen, Indiana DOT, pers. comm.
Alaska Hwy 1 (58.0–79.0) (two-lane), AK, USA	33.8	AR, MSR (2006)	0.56 moose (\$17 226)	\$17 226	Rick Ernst, Kenai National Wildlife Refuge, pers. comm.
I-95 (near Medway) (four-lane), ME, USA	32.2	AR (2005)	0.06 deer (\$397) 0.53 moose (16 303)	\$16 700	Duane Brunell, Maine DOT, pers. comm.
Hwy 1, Banff National Park (Phase 3b) (two-lane), AB, Canada	28.1	AR, R, PWI (2005)	0.60 deer (\$3970) 0.32 elk (\$5595) 0.07 moose (\$2153)	\$11 718	Shelagh Wrazej, Parks Canada, pers. comm.
Route 169 (1.0–61.0) (two-lane), Laurentides Wildlife Reserve, QC, Canada	61.0	HM, AR (2003)	0.33 moose (\$10 151)	\$10 151	Yves Leblanc, Tecsalt Inc., pers. comm.
I-90 (55.0–70.0) (four-lane), Snoqualmie Pass, WA, USA	24.1	HM (2005)	0.70 deer (\$4632) 0.25 elk (\$4371)	\$9003	Victoria Fursman, Washington DOT, pers. comm.
MT Hwy 83 (two-lane), MT, USA	76.9	HM (1998–2003)	1.19 deer (\$7287) 0.01 elk (\$176)	\$7463	Huijser et al. 2006b
Highway 93 S (two-lane), Kootenay National Park, BC, Canada	34.2	AR, PWI (2005)	0.41 deer (\$2713) 0.03 moose (\$923)	\$3636	Shelagh Wrazej, Parks Canada, pers. comm.

Fig. 8. The costs (in 2007 US\$) associated with wildlife–vehicle collisions (deer and elk) along the two-lane MT Hwy 83 (mile reference posts 0.0–47.8) per year (average 1998–2003), and the threshold values (at 3% discount rate) that need to be met in order to have the benefits of individual mitigation measures exceed the costs over a 75-year time period. Note that the costs at each 0.1 mile concerned and five adjacent 0.1 mile units were summed (0.6 mile = 1 km) to estimate the costs per kilometer.



Elevated roadways and road tunnels have very high threshold values, suggesting that these measures are unlikely to be implemented based on an economic analysis of deer-, elk-, or moose–vehicle collisions alone. Elevated roadways or road tunnels appear to be put in place primarily because of landscape characteristics (e.g., the presence of a mountain or a canyon), ecosystem processes (e.g., the flow of large amounts of water in rivers), and perhaps

concerns for specific threatened or endangered species (e.g., Evink 2002, Huijser et al. 2007b). This also illustrates another limitation of our cost–benefit analyses; it is primarily focused on the costs and benefits of collisions with large ungulates and the impacts on human safety. If other parameters are included it may change the threshold values substantially.

The threshold values for the individual mitigation measures are based on the mitigation of relatively long road sections (e.g., at least several kilometers or miles). This is especially important for the mitigation measures that include safe crossing opportunities (one safe crossing opportunity per 2 km, see Appendix 1). In this context, it is also critical to consider the habitat and home range of the species concerned to prevent individual animals from simply walking to the beginning or end of a mitigated road section to cross the road there, potentially reducing the effectiveness of the mitigation measure (see, e.g., Huijser et al. 2008).

The costs associated with collisions with large ungulates are a current estimate and may be subject to change when additional studies are conducted. The same is true for the costs (e.g., price of fuel, concrete, and steel) and effectiveness of the individual mitigation measures. In addition, mass production, the use of less expensive materials and construction techniques, and incorporating mitigation measures early in the planning of road (re-) construction projects may further reduce the costs for mitigation measures. Furthermore, there may be biases in our estimates for the costs of collisions with large ungulates. For example, the cost estimates for deer-, elk-, and moose-vehicle collisions only relate to the collisions reported to the insurance industry or to law enforcement agencies, and one could argue that unreported collisions are likely to be less costly than reported collisions. Therefore, we may have overestimated the average costs of a collision with a deer, elk, or moose. On the other hand, insurance industry reports and police accident reports may underestimate ungulate-vehicle collisions by about 50% (Tardif and Associates Inc. 2003, Riley and Marcoux 2006), and law enforcement agencies may only record a fraction (14%) of the deer-vehicle collisions reported to the insurance industry (Donaldson and Lafon 2008). Furthermore, in most states and provinces in the United States and Canada, no accident report is filled out by law enforcement agencies if the estimated vehicle damage is less than US\$1000 (Huijser et al. 2007b). The most conservative approach would be to only include collisions that were reported to the insurance industry or law enforcement agencies and screen the data for potential duplicates. However, based on the studies cited above, it is clear that such an approach may lead to a serious underestimation of the actual costs of collisions with large ungulates, and one may choose to include carcass reports,

recognizing that although this may overestimate the average costs associated with a deer-, elk-, or moose-vehicle collision, it may still underestimate the actual number of ungulate-vehicle collisions by about 50%. Crash and carcass data collection can be much improved (see also Huijser 2007b), which would greatly benefit the accuracy of cost-benefit analyses that evaluate the economic feasibility of mitigation measures.

CONCLUSION

We believe that the cost-benefit model presented in this paper can be a valuable decision-support tool for transportation agencies and natural resource management agencies when deciding on the implementation of mitigation measures to reduce ungulate-vehicle collisions. The tool allows for the selection of the appropriate road sections as well as the type of mitigation measure. The results suggest that there must be many road sections in the United States and Canada where the benefits of mitigation measures exceed the costs and where the mitigation measures would help society save money and improve road safety for humans and wildlife. Mitigation measures that include safe crossing opportunities for wildlife may not only substantially reduce road mortality, but also allow for wildlife movements across the road. This connectivity is essential to the survival probability of the fragmented populations for some species in some regions.

Responses to this article can be read online at:
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Appendix 1. Cost Estimates for Mitigation Measures

[Please click here to download file 'appendix1.pdf'.](#)

Appendix 2. Cost Estimates for Deer-, Elk-, and Moose-Vehicle Collisions

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