Update and expansion of the WVC mitigation measures and their cost-benefit model

NDOT Research Report No.701-18-803 TO 1 Part 3

Wildlife Vehicle Collision Reduction and Habitat Connectivity Pooled Fund Study, TPF-5(358)

REDUCE Wildlife Vehicle Collisions

INCREASE Habitat Connectivity

IMPLEMENT Cost Effective Sollutions

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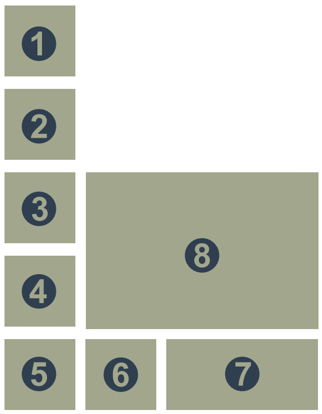

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Report No. 701-18-803 TO 1 Part 3

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PART 3 - COST EFFECTIVE SOLUTIONS: COST-BENEFIT ANALYSES OF MITIGATION MEASURES ALONG HIGHWAYS FOR LARGE ANIMAL SPECIES: AN UPDATE AND AN EXPANSION OF THE 2009 MODEL

September 2022

Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712

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16. Abstract

This report contains an update and an expansion of a cost-benefit model for wildlife-vehicle collisions and associated mitigation measures along highways, that was originally calculated in 2007 US$ and published in 2009. The direct cost values (vehicle repair, human injuries, human fatalities) were updated for deer, elk, and moose, and expanded by including additional species: gray wolf (*Canis lupus*), grizzly bear (*Ursus arctos*), and free ranging or feral domesticated species including cattle, horse, and burro. The costs associated with collisions were also expanded by including passive use, or non-use values associated with the conservation value of selected wild animal species. The total costs (in 2020 US$) associated with a collision with deer, elk and moose were about 2-3 times (direct costs only) or about 3-4 times higher (direct costs and passive use values combined) compared to the values in 2007 US$. The passive use costs associated with threatened species (wolf, grizzly bear) were higher or much higher than the direct costs. The costs associated with mitigation measures (especially fences and wildlife crossing structures) were also updated and supplemented with new data. New cost-benefit analyses generated updated or entirely new threshold values for deer, elk, moose, and grizzly bear. If collisions with these large wild mammal species reach or surpass the threshold values, it is economically defensible to install the associated type and combination of mitigation measures, both based on direct use and passive use parameters and their associated values. The trend in increasing costs associated with vehicle repair costs, costs associated with human injuries and fatalities, and through including passive use values for wildlife is that we learn that the implementation of effective mitigation measures can be considered earlier and more readily than based on the cost-benefit model published in 2009.

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Cost–Benefit Analyses of Mitigation Measures Along Highways for Large Animal Species: An Update and an Expansion of the 2009 Model

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For the following larger project:

Wildlife Vehicle Collision (WVC) Reduction and Habitat Connectivity

Task 1 – Cost Effective Solutions

Transportation Pooled-Fund Project TPF-5(358)

(Administered by the Nevada Department of Transportation)

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DISCLAIMER

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SUMMARY

Wildlife-vehicle collisions, especially with deer (*Odocoileus* spp.), elk (*Cervus canadensis*), and moose (*Alces americanus*) are numerous and have shown an increasing trend over the last several decades in the United States and Canada. The costs associated with the average deer-, elk-, and moose-vehicle collision was calculated in 2007 US$ and published in 2009. This report contains an update and an expansion to that cost-benefit model.

The direct cost values (vehicle repair, human injuries, human fatalities) were updated for deer, elk, and moose, and expanded by including additional species: gray wolf (*Canis lupus*), grizzly bear (*Ursus arctos*), and free ranging or feral domesticated species including cattle, horse, and burro. The costs associated with collisions were also expanded by including passive use, or non-use values associated with the conservation value of selected wild animal species. The total costs (in 2020 US$) associated with a collision with deer, elk and moose were about 2-3 times (direct costs only) or about 3-4 times higher (direct costs and passive use values combined) compared to the values in 2007 US$. The passive use costs associated with threatened species (wolf, grizzly bear) were higher or much higher than the direct costs.

The costs associated with mitigation measures (especially fences and wildlife crossing structures) were also updated and supplemented with new data. New cost-benefit analyses generated updated or entirely new threshold values for deer, elk, moose, and grizzly bear. If collisions with these large wild mammal species reach or surpass the threshold values, it is economically defensible to install the associated type and combination of mitigation measures, both based on direct use and passive use parameters and their associated values. The trend in increasing costs associated with vehicle repair costs, costs associated with human injuries and fatalities, and through including passive use values for wildlife is that we learn that the implementation of effective mitigation measures can be considered earlier and more readily than based on the cost-benefit model published in 2009.

1 INTRODUCTION

Wildlife-vehicle collisions, especially with deer (*Odocoileus* spp.), elk (*Cervus canadensis*), and moose (*Alces americanus*) are numerous and have shown an increasing trend over the last several decades in the United States and Canada. The costs associated with the average deer-, elk-, and moose-vehicle collision was calculated by Huijser et al. (2009). The cost estimates included 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, Huijser et al. (2009) reviewed the effectiveness and costs of 13 mitigation measures considered effective in reducing collisions with large ungulates. Huijser et al. (2009) 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.

This report contains an update and an expansion to the cost-benefit model originally developed by Huijser et al. (2009). The direct costs values (vehicle repair, human injuries, human fatalities) were updated for deer, elk, and moose, and expanded by including additional species: gray wolf (*Canis lupus*), grizzly bear (*Ursus arctos*), and free ranging or feral domesticated species including cattle, horse, and burro. The costs associated with collisions were also expanded by including passive use, or non-use values associated with the conservation value of selected wild animal species. The costs associated with mitigation measures (particularly fences and crossing structures) were also updated and supplemented with new data. New cost-benefit analyses generated updated threshold values for deer, elk, moose, and grizzly bear. If collisions with these large wild mammals reach or surpass the threshold values, it is economically defensible to install the associated type and combination of mitigation measures, both based on direct use and passive use parameters and their associated values.

2 COST ESTIMATES FOR LARGE MAMMAL-VEHICLE COLLISIONS

The researchers estimated the cost of the average collision with a deer (white-tailed deer (*Odocoileus virginianus*) and mule deer (*O. hemionus*) combined), elk (*Cervus canadensis*), moose (*Alces americanus*), gray wolf (*Canis lupus*), grizzly bear (*Ursus arctos*), and free ranging or feral domesticated species including cattle, horse, and burro. Unless indicated otherwise, all cost estimates were expressed as US$ as reported in the cited work. For our cost-benefit analyses (see later) we converted all costs to 2020 US$, the last year vehicle repair costs were available for deer-vehicle collisions (U.S. Department of Labor 2022). The components included in our cost estimate were vehicle repair costs, costs associated with human injuries and fatalities (see also e.g. Bissonette et al. 2008), and passive use costs.

2.1 Vehicle repair costs associated with deer-, elk-, and moose-vehicle collisions

Data on vehicle repair costs for collisions with deer were acquired from the literature between 2005-2020 (Appendix A, Figure 1). Based on a regression analysis, vehicle repair costs after a collision with a deer was estimated at US$ 4,802 in 2020 (Figure 1). This is a US$ 2,087 (76.84%) increase from the US$ 2,716 in 2007 (based on the regression analysis), or a US$ 1,952 (68.48%) increase from US$ 2,850 in 2007 (based on Huijser et al. 2009). The steep increase in vehicle repair costs is likely associated with higher repair costs for modern vehicles that have airbags and more electronics (e.g. sensors), but possibly also because of a growing proportion of relatively large and more expensive vehicles on the roads in the USA (i.e. truck SUVs, car SUVs, and pickups), and declining proportion of relatively small and less expensive vehicles (i.e. sedans and wagons) (EPA 2021).

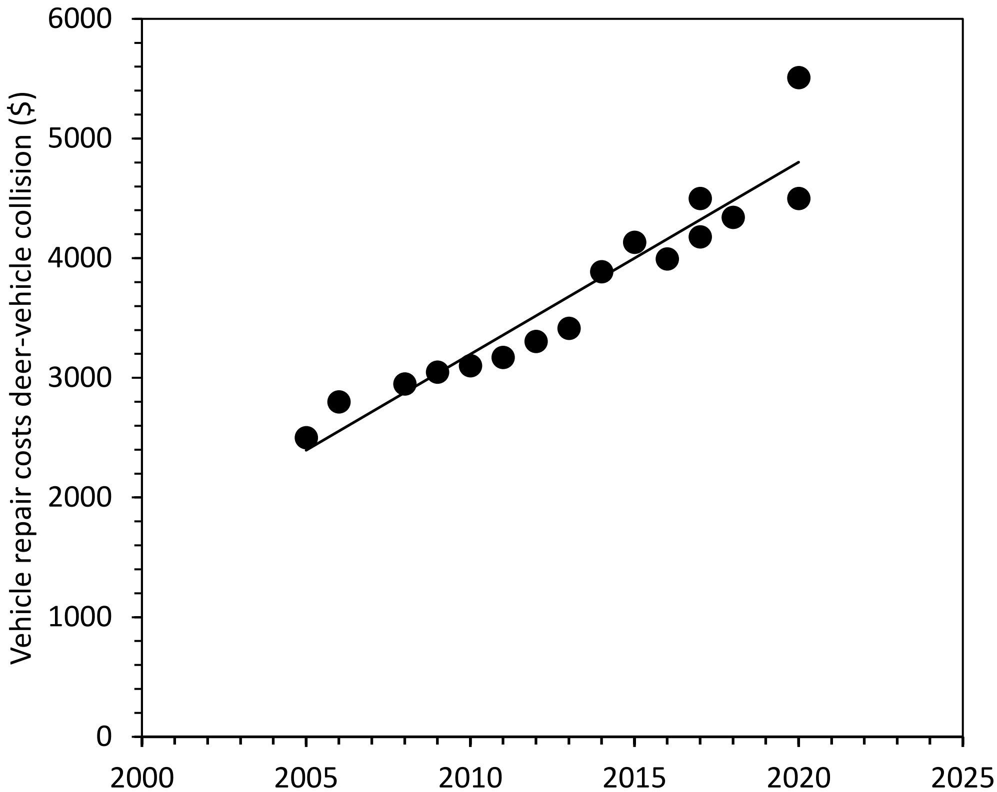

Figure 1: Vehicle repair costs associated with a collision with a deer. Linear regression equation: Cost = -319427.7897 + (160.5099 * Year). R2 =0.9014, P<0.0001, Cost increase per year is US $160.51.

There were no recent data available for vehicle repair costs for elk and moose, nor for gray wolf, grizzly bear, cattle, horse, or burro. To estimate the vehicle repair costs associated with a collision for elk and moose, a 68.48% increase (see previous paragraph) was applied to the estimated costs from 2007 (Huijser et al. 2007) (Table 1).

Table 1: Estimated vehicle repair costs in 2007 and 2020 for deer, elk, and moose.

	2007	2020
Deer	$2,850	$4,802
Elk	$4,550	$7,666
Moose	$5,600	$9,435

2.2 Probability of vehicle damage

In Nova Scotia, the percentage of collisions involving white-tailed deer which resulted in property damage was estimated at 90.2% (3,524 collisions with property damage out of 3,905 collisions) (Tardif & Associates Inc. 2003). In Utah this percentage was estimated at 94% (Romin & Bissonette 1996). There were no similar data available for elk or moose. For these analyses the percentage of collisions resulting in property damage was assumed to be 92% for collisions with deer and 100% for collisions with elk and moose as elk and moose are much larger than deer and thus more likely to result in vehicle damage. The cost associated with vehicle repair for the average deer-, elk-, and moose-vehicle collision, corrected for the probability that a collision indeed results in vehicle damage, is US$ 4,418 for deer, US$ 7,666 for elk, and US$ 9,435 for moose (Table 2).

Table 2: Estimated vehicle repair costs in 2007 and 2020, corrected for the likelihood that a collision results in vehicle damage, for deer, elk, and moose.

	2007	2020
Deer	$2,622	$4,418
Elk	$4,550	$7,666
Moose	$5,600	$9,435

2.3 Human injures

The percentage of white-tailed deer-vehicle collisions resulting in human injuries was estimated at 2.8% in Michigan (12 injuries from 60,875 collisions) (SEMCOG 2007), 3.8% in the US Midwest (4,724 injuries from 125,608 collisions) (Knapp et al. 2004); 4% in Ohio (general review in Schwabe et al. 2002), 4% (review in Conover et al. 1995), 7.7% in Ohio (10,983 injuries from 143,016 collisions) (Schwabe et al. 2002), 9.7% in Nova Scotia (378 injuries from 3,905 collisions) (Tardif & Associates Inc. 2003), and 12.22% in California (847 out of 6,922) (Huijser & Begley 2019). Similar data could not be retrieved for elk. The percentage of moose-vehicle collisions resulting in human injuries was estimated at 18% in Newfoundland and Labrador (Government of Newfoundland and Labrador 1997); 21.8% in Newfoundland (363 injuries from 1,662 collisions) (Tardif & Associates Inc. 2003); 20% in rural Alaska (Thomas 1995); 23% in Maine (Huijser et al. 2007); and, 23% in Anchorage, Alaska (158 injuries from 519 collisions) (Garrett and Conway 1999).

The ratio of moose-vehicle collisions to human injuries was estimated at 1:0.201 in Newfoundland (Rattey & Turner 1991) and 1:0.304 in Anchorage, Alaska (Garrett & Conway 1999). The ratios are higher than the percentages because more than one person may be present in a car, and multiple people may be injured in one collision. Based on the data presented above, it was assumed that an animal-vehicle collision resulted in an average of 0.05 human injuries for deer, 0.10 for elk, and 0.20 for moose.

The costs associated with human injuries depend on the severity of the injury (U.S. DOT 2022a) and the methodology is similar to that of determining the Value of a Statistical Life (VSL) (U.S. DOT 2013). The VSL is based on the "additional cost that individuals would be willing to bear for improvements in safety (that is, reductions in risks) that, in the aggregate, reduce the expected number of fatalities by one" (U.S. DOT 2013). Thus, "it is not the valuation of life as such, but the valuation of reductions in risks" (U.S. DOT 2013). The costs are listed below based on the "KABCO" injury scale that is often used by law enforcement personnel that records the crash data (Table 3). Maine DOT has published data on how deer-vehicle and moose-vehicle crashes that have resulted in human injuries are distributed over the three different categories for human injuries (Possible injury (C), Non-incapacitating injury (B), and Incapacitating injury (A) (Maine DOT 2021) (Table 3). The authors of this report calculated the proportion of the deer-vehicle and moose-vehicle collisions over these three categories (Table 3). This allowed the authors to calculate the costs for a human injury associated with a deer-vehicle (US$ 122,327) and a moose-vehicle collision (US$ 145,787) (in 2020 US$). The cost for a human injury associated with an elk-vehicle collision was assumed to be midway that for a deer and a moose-vehicle collision (US$ 134,057).

Table 3: The costs associated with different categories for human injuries and human fatality, and the frequency distribution of deer-vehicle and moose-vehicle crashes across the three categories for human injuries. Note that "No injury (O)" and "Killed (K)" were excluded as here we aimed to calculate the costs associated with human injuries. Furthermore, injured (U) was excluded because this category was not used in Maine DOT (2021).

KABCO category	Cost (in 2020 US$)[*1]	Deer crashes (N)[*2]	Moose crashes (N)[*2]	Deer crashes (proportion)	Moose crashes (proportion)
O No injury	$3,900	N/A	N/A	N/A	N/A
C Possible injury	$77,200	454	102	0.658926	0.502463
B Non-incapacitating	$151,100	201	85	0.291727	0.418719
A Incapacitating	$554,800	34	16	0.049347	0.078818
K Killed	$11,600,000	N/A	N/A	N/A	N/A
U Injured (severity unknown)	$210,300	N/A	N/A	N/A	N/A
Total		689	203	1	1

[*1] U.S. DOT (2022a)
[*2] Maine DOT (2021)

An animal-vehicle collision resulted in an average of 0.05 human injuries for deer, 0.10 for elk, and 0.20 for moose (see earlier). Therefore, the average deer-vehicle collision was allocated US$ 6,116 (0.05* US$ 122,327) to include the costs associated with the occasional human injury. Similarly, these values were US$ 14,579 for elk and US$ 26,811 for moose.

2.4 Human fatalities

The percentage of white-tailed deer-vehicle collisions resulting in human fatalities was estimated at 0.009% in Ohio (14 collisions with human fatalities from 143,016 collisions) (Schwabe et al. 2002); 0.020% (12 fatalities from 60,875 collisions) (SEMCOG 2007); 0.029% in North America (review in Schwabe et al. 2002); 0.026% in the US Midwest (33 collisions with human fatalities from 125,608 collisions) (Knapp et al. 2004); 0.051% in Nova Scotia (2 collisions with human fatalities from 3,905 collisions) (Tardif & Associates Inc. 2003), and 0.188% in California (13 out of 6,922 collisions) (Huijser & Begley 2019). Similar data could not be retrieved for elk. The percentage of moose-vehicle collisions resulting in human fatalities was estimated at 0% in Anchorage, Alaska (0 fatalities from 519 collisions) (Garrett & Conway 1999); 0.26% in Newfoundland (14 fatalities from 5,422 collisions) (Joyce & Mahoney 2001), 0.36% in Newfoundland (6 collisions with human fatalities from 1662 collisions) (Tardif & Associates Inc. 2003), 0.45% in Newfoundland (3 fatalities from 661 collisions) (Rattey & Turner 1991); 0.43% in Maine (Huijser et al. 2007); and 0.50% in rural Alaska (Thomas 1995). Based on the data presented above, it was assumed that an animal-vehicle collision resulted in an average of 0.0003 (deer), 0.0020 (elk), and 0.0040 (moose) human fatalities. When these proportions are combined with the cost associated with a human fatality (i.e. the Value of a Statistical Life (VSL), US$ 11,600,000 in 2020 (U.S. Department of Transportation 2022b), it results in a cost estimate for human fatalities of US$ 3,480 (deer), US$ 23,200 (elk), and US$ 46,400 (moose) for each collision (all in 2020 US$). For comparison, the 2007 estimates were US$1,002 (deer), US$6,683 (elk), and US$13,366 (moose) with the cost of a human life of US$ 3,341,468 (Huijser et al. 2009) (all in 2007 US$).

2.5 Passive use values

Passive use, also known as non-use values, are the values individual people place on the existence of a given animal species or population as well as the bequest value of knowing that future generations will also benefit from preserving the species (Duffield & Neher 2019). The authors summarized the current literature of passive use value estimates for deer, elk, gray wolf, and grizzly bear, and provided per-animal passive use values (Table 4). If possible, the authors used passive use values for areas outside of protected areas such as National Parks. This is because most highways and most highway mitigation measures are outside of National Parks. However, if a major highway runs through a protected area, or if animals roam both inside and outside a protected area and are impacted by a highway outside a protected area, passive use values for protected areas are defensible.

Table 4: Passive use values for large wild mammal species.

Species	Passive use value (2019 US$)	Passive use value (2020 US$)[*1]	Notes	Average Passive use value (2020 US$)	Source
White-tailed deer	$4,952	$5,075	Outside a protected area	$5,075.14	Duffield & Neher 2021
Elk	$36,925	$37,843	In a protected area	$27,751	Duffield 1991, Duffield & Neher 2019
	$17,230	$17,658	In a protected area		Duffield 1991, Duffield & Neher 2019
Wolf	$2,002,700	$2,052,499[*2]	In a protected area, National	$40,342	USFWS 1994, Duffield & Neher 2019
	$22,300	$22,855	In a protected area, Regional		USFWS 1994, Duffield & Neher 2019
	$56,427	$57,830	Outside a protected area		Duffield et al. 2006, Duffield & Neher 2019
Grizzly bear	$4,133,000	$4,235,770	For reintroduction	$4,235,770	USFWS 2000, Duffield & Neher 2019

[*1] Conversion from 2019 to 2020 US$ based on U.S. Department of Labor (2022).
[*2] Not used in the calculation for the average as it relates to Yellowstone National Park.

2.6 Total costs associated with large wild ungulate-vehicle collisions (in 2020 US$).

The total costs associated with the average large wild ungulate-vehicle collision, based on vehicle repair costs, human injuries, and human fatalities is US$ 14,014 for deer, US$ 45,445 for elk, and US$ 82,646 for moose (Table 5). Other potential direct costs not included in this table are towing, accident attendance and investigation, and carcass removal and disposal. The hunting value of the animal concerned (a “direct use” value), was also not included. However, these are likely in the hundreds of dollars for each category, rather than in the thousands or tens of thousands, and are unlikely to substantially increase the cost estimates (see Huijser et al. 2009). Based on the size and weight of the different species (see Appendix B) and the associated vehicle repair costs and costs associated with the occasional human injury and fatality, wolf and grizzly bear were considered similar to deer, burro was considered similar to elk, and cattle and horse were considered similar to moose.

Table 5: Total costs associated with large wild ungulate-vehicle collisions (in 2020 US$).

	Costs per collision							
Cost category	Deer	Elk	Moose	Gray wolf	Grizzly bear	Cattle	Horse	Burro
Direct costs								
Vehicle repair	$4,418	$7,666	$9,435	$4,418	$4,418	$9,435	$9,435	$7,666
Human injuries	$6,116	$14,579	$26,811	$6,116	$6,116	$26,811	$26,811	$14,579
Human fatalities	$3,480	$23,200	$46,400	$3,480	$3,480	$46,400	$46,400	$23,200
Sub total	$14,014	$45,445	$82,646	$14,014	$14,014	$82,646	$82,646	$45,445
Passive use value	$5,075	$27,751	$27,751	$40,342	$4,235,770	?	?	?
Total	$19,089	$73,196	$110,397	$54,356	$4,249,784	$82,646	$82,646	$45,445

The direct costs associated with vehicle repair, human injuries and human fatalities increased by a factor 2.12 (for deer), 2.60 (for elk) and 2.69 (for moose), compared to the 2007 values (Huijser et al. 2009). When the passive use values are included, these factors increase to 2.88 (for deer), 4.19 (for elk) and 3.59 (for moose), compared to the 2007 values (Huijser et al. 2009).

3 DOES THE SEVERITY OF LARGE ANIMAL-VEHICLE CRASHES REDUCE OVERTIME?

Vehicle repair costs associated with deer-vehicle collisions have increased substantially over the last few decades (see Chapter 2). This is likely associated with higher repair costs for modern vehicles that have airbags and more electronics (e.g. sensors), but possibly also because of a growing proportion of relatively large and more expensive vehicles on the roads in the USA (i.e. truck SUVs, car SUVs, and pickups), and declining proportion of relatively small and less expensive vehicles (i.e. sedans and wagons) (EPA 2021). Note that in the context of animal-vehicle collisions versus other types of crashes, the risk of human fatalities for occupants of large vehicles such as SUVs and pickup trucks is not necessarily lower than that for occupants of smaller cars such as passenger cars (Abra et al. 2019). Thus, while vehicle repair costs associated with large mammal-vehicle collisions have increased, it may be that this is somewhat compensated by fewer and less severe human injuries and fewer human fatalities. To investigate we used data summarized by Maine DOT for deer-, and moose-vehicle collisions between 2006 and 2020 (Maine DOT 2011, 2016, 2021).

The researchers compiled the frequency of deer- and moose-vehicle collisions per years across the different human injury categories (KABCO scale) for deer and moose. The researchers then calculated the proportion of the crashes across the different categories and conducted a series of linear regression analyses to investigate whether the slope of the injury categories deviated from zero (Table 6). For deer, both the proportion of incapacitating and non-incapacitating human injuries significantly declined ($P<0.05$) between 2006-2020 whereas the "proportion of property damage only" crashes significantly increased (Table 6, Figure 2). The estimated change in the proportion of incapacitating injuries (A) per year is -0.0001 (a decrease), for non-incapacitating injuries (B) per year it is -0.0003 (a decrease), whereas the proportion of crashes that resulted in "property damage only" (PDO) increased by 0.0003 per year. For moose, the proportion of non-incapacitating human injuries significantly declined between 2006-2020 whereas the "proportion of property damage only" crashes significantly increased (Table 6, Figure 3). Overall, the results confirm the hypothesis that while large mammal-vehicle collision repair costs have increased, there has been a decrease in the proportion of crashes with human injuries and an increase in the proportion of crashes that resulted in "property damage only". Interestingly, there was no change in the proportion of crashes with human fatalities, and for the largest of the 2 species (moose vs. deer), there was also no change in the proportion of incapacitating injuries. On the other hand, the increase in the proportion of moose-vehicle crashes that resulted in "property damage only" (slope 0.0044) was much stronger than for deer-vehicle crashes (slope 0.0003).

Table 6: Output linear regression analyses for the different human injury categories (KABCO scale) associated with deer- and moose-vehicle collisions (Based on Maine DOT 2011, 2016, 2021). For P>0.05 the estimated value for slope is not shown and set to "zero".

	Parameter		Fatal crash (K)	Incapacitating injury (A)	Non-incapacitating injury (B)	Possible injury (C)	Property damage only (PDO)
Deer	R^2		0.1602	0.5112	0.3438	0.006	0.2690
	P		0.1394	0.0027	0.0216	0.7846	0.0476
	Slope		zero	-0.0001	-0.0003	zero	0.0003
Moose	R^2		0.0698	0.0375	0.4181	0.1632	0.6508
	P		0.3414	0.4892	0.0092	0.1353	0.0003
	Slope		zero	zero	-0.0032	zero	0.0044

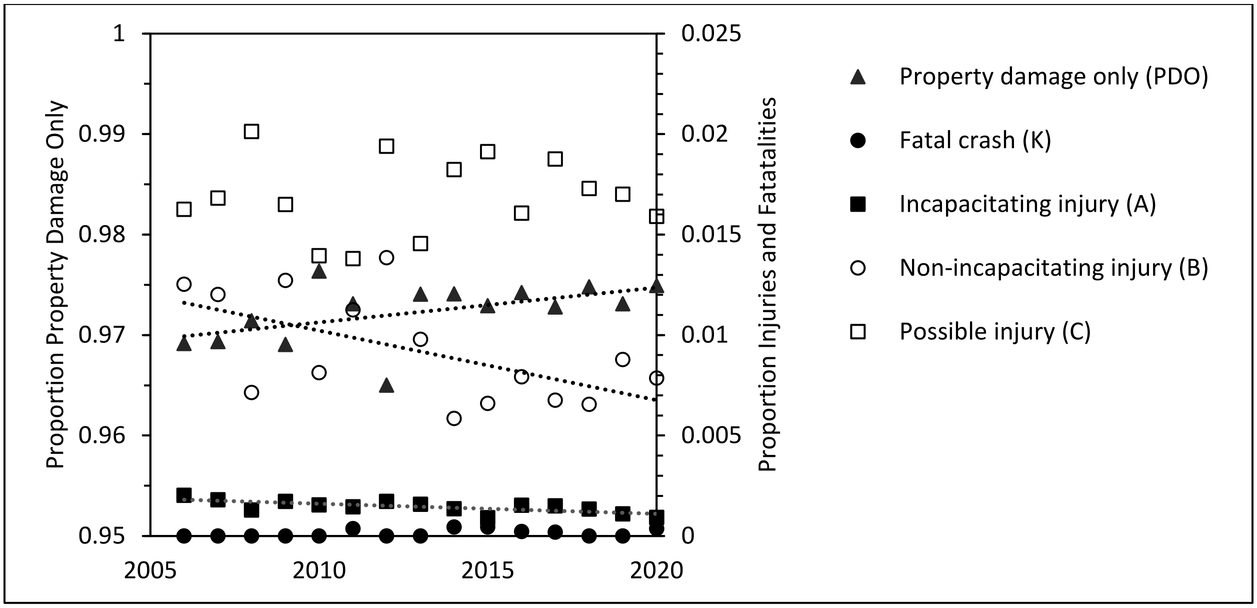

Figure 2: The proportion of crashes in each human injury category (KABCO scale) for white-tailed deer-vehicle crashes between 2006-2020 (based on Maine DOT 2011, 2016, 2020). The injury categories for which the slope of the line is significantly different from zero (positive or negative) show the line in the graph. If the slope was not significantly different from zero, no line is shown.

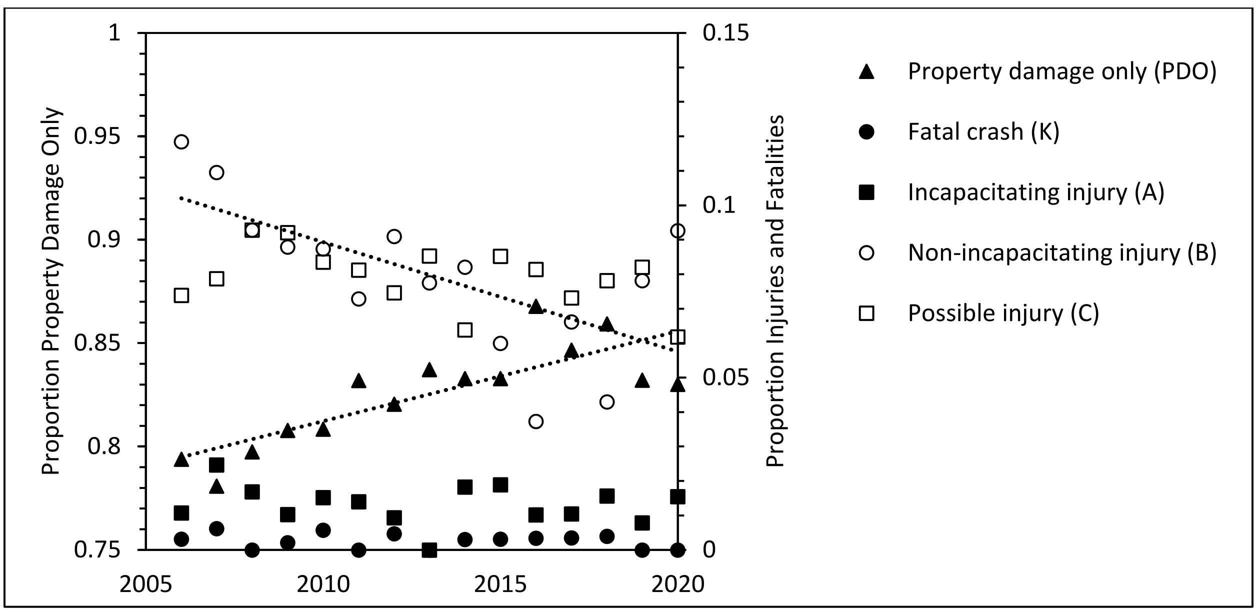

Figure 3: The proportion of crashes in each human injury category (KABCO scale) for moose-vehicle crashes between 2006-2020 (based on Maine DOT 2011, 2016, 2020). The injury categories for which the slope of the line is significantly different from zero (positive or negative) show the line in the graph. If the slope was not significantly different from zero, no line is shown.

4 COSTS OF MITIGATION MEASURES

The researchers estimated the costs of selected mitigation measures aimed at mitigating large mammal-vehicle collisions and at providing safe crossing opportunities for wildlife through wildlife crossing structures. The researchers included large mammal fences, and different sized culverts, bridges, and overpasses (Table 7). Sources included peer-reviewed article, scientific report, personnel from Departments of Transportation, news articles, and some of the dimensions were estimated from aerial images.

The researchers noted the construction year and associated costs. For our cost-benefit analyses (see later) we converted all costs to 2020 US$, the last year vehicle repair costs were available for deer-vehicle collisions (U.S. Department of Labor 2022). The components included in our cost estimate included construction costs, but some also included design costs, traffic control, and project oversight.

Table 7: Estimated construction costs for large mammal fences and different types and dimensions of wildlife crossing structures (in US$ 2020). Bissonette & Hammer 2000; Huijser et al. 2009; 2016a; Arizona Daily Star 2015; Clevenger & Huijser 2021; Pers. com. Pat Basting and Joe Weigand, Montana Department of Transportation; Jeff Gagnon, Arizona Game and Fish Department; Terry McGuire, McGuire Consulting; Greg Schonert, North Dakota Department of Transportation; Nova Simpson, Nevada Department of Transportation. The dimensions are from the animal's perspective, e.g. width = the road length covered by the structure, height = the height between the ground and the ceiling of an underpass, length = the distance that animals travel through or on top of the structure to reach the other side of the road (i.e. the width of the road).

Structure type	Mean	SD	Median	Minimum	Maximum	N
Fence, 2.4-2.7 m tall, no apron, for 1 km on both sides rd	$91,064	$20,651	$98,869	$67,648	$106,675	3
Fence, 2.4-2.7 m tall, with apron, for 1 km on both sides rd	$169,667	$25,334	$170,231	$139,792	$198,415	4
Jump-out	$10,124	$5,946	$8,130	$5,432	$16,811	3
Metal culvert, width 1.8-2.4 m, height 1.2-2.4 m, length 29-40 m	$134,862	$41,401	$125,670	$96,753	$191,355	4
Box culvert, width 1.2-2.4 m, height 1.2-2.4 m	$102,895	$22,651	$102,824	$75,942	$139,879	6
Box culvert, width 3.6 m, height 2.4 m, length 24-52 m	$485,105	$109,586	$461,192	$389,451	$604,673	3
Box culvert, width 6.1 m, height 4.0 m, length 30 m	$1,067,257	$45,894	$1,040,760	$1,040,760	$1,120,250	3
Underpass, width 7.0-8.5 m, 3.7-5.6 m high, length 15-52 m	$485,444	$159,899	$474,021	$253,679	$983,875	24
Bridge, width 14-30 m, length 14-40 m	$1,403,804	$1,174,429	$953,324	$181,402	$3,074,610	7
Bridge, width 100-120 m, length 12-17 m	$3,092,367	$904,394	$3,092,367	$2,452,864	$3,731,870	2
Overpass, 15-30 m wide, length about 70 m	$1,740,852	$327,960	$1,904,832	$1,248,912	$1,904,832	4
Overpass, 50-60 m wide, length 63-123 m	$4,273,104	$1,577,583	$4,973,694	$2,243,730	$6,559,168	8

5 COST-BENEFIT ANALYSES

Following the procedures in Huijser et al. (2009) the authors conducted a series of cost benefit analyses (all in 2020 US$) for selected measures aimed at mitigating large mammal-vehicle collisions and at providing safe crossing opportunities for wildlife through wildlife crossing structures. The researchers used the total costs associated with a collision: direct costs associated with vehicle repair, human safety, and passive use value (see Table 5). Species for which the analyses were conducted included deer, elk, moose, and grizzly bear. The latter species was included because of its relatively high passive use value and high total costs associated with direct road mortality of an individual. Consistent with Huijser et al. (2009) the analyses were conducted over a 75-year period and for 3 different discount rates (1%, 3% and 7%). Four different types and combinations of mitigation measures were included in the analyses:

1. Fence without apron (without dig barrier).
2. Fence with apron (with dig barrier).
3. Fence with apron, large mammal underpasses once every 2 km (width 7.0-8.5 m, 3.7-5.6 m high), and 7 jump-outs per km road length.
4. Fence with apron, large mammal underpasses once every 2 km (width 7.0-8.5 m, 3.7-5.6 m high), large mammal overpasses once every 24 km (50-60 m wide, replaces an underpass once every 24 km), and 7 jump-outs per km road length.

The first two types and combinations of mitigation measures only include wildlife fences (with and without an apron). A well designed, constructed, and maintained fence can be expected to reduce collisions with large mammals by at least 80% if it is implemented over a road length of at least 5 km (Huijser et al. 2016b). However, a fence alone would result in an absolute barrier in the landscape at least for the species for which the fence is designed, and potentially also other species. Making the road into a (near) absolute barrier for wildlife implies that the resulting increased habitat fragmentation and barrier effect of the infrastructure, and potential associated reduced population persistence, are not a concern. This can be considered an ethical problem (Moore et al. 2021). Therefore, the authors of this report do not suggest implementing wildlife fences without safe and effective crossing opportunities for wildlife (i.e. in most cases this means including wildlife crossing structures). The fences as a stand-alone mitigation measure were only included in the analyses as a reference for the thresholds for measures that do include wildlife crossing structures.

For the costs of fences, crossing structures and jump-outs, the researchers used the median costs (Table 7), and then standardized these costs to costs per km (Table 8). The length of the structures (i.e. road width) varied and included both 2- and 4-lane highways. Thus, the costs are on the high side for 2-lane highways and on the low side for 4-lane highways. Some costs only occurred once (e.g. design), whereas others occurred every year (maintenance). Construction costs occurred at the start (year zero), and at the end of the lifespan (unless the end of the life span was in the 75th year). Removal costs occurred at the end of the lifespan of the feature, including in the 75th year. Effectiveness of the wildlife fence was set at 86% reduction in large mammal-vehicle collisions (see Huijser et al. 2009).

Table 8: The costs for the different types and combinations of mitigation measures standardized per km per year (in 2020 US$). These costs are based on the median costs for each measure (see Table 7).

Feature	Costs per km road length (in 2020 US$)			
	Fence (no apron)	Fence (apron)	Fence (apron), underpass, jump-outs	Fence (apron), under- and overpass, jump-outs
Fence design (once)	$10,000	$10,000	$10,000	$10,000
Fence construction (every 25 yrs)	$98,869	$170,231	$170,231	$170,231
Fence maintenance (every year)	$1,000	$1,000	$1,000	$1,000
Fence removal (every 25 yrs)	$15,000	$15,000	$15,000	$15,000
Jump-outs (once)			$56,910	$56,910
Crossing structure design (once)			$50,000	$50,000
Crossing structure maintenance (every year)			$2,000	$2,000
Crossing structure removal (once)			$50,000	$50,000
Underpass construction (once)			$237,011	$227,056
Overpass construction (once)				$207,237

The researchers calculated the thresholds or "break-even values" for the different types and combinations of mitigation measures (Table 9). The thresholds were expressed in 2020 US$ as well as the number of collisions for the 4 different species per km per year required to equal the costs of the 4 different types and combinations of mitigation measures. For example, for 3% discount rate, and for a combination of wildlife fences, a large mammal underpass once every 2 km, and jump-outs, the break-even point for deer is 1.5 collisions per kilometer per year. This is about half of the 3.2 threshold reported by Huijser et al. (2009). This illustrates that the costs associated with collisions (i.e. vehicle repair, human injuries, human fatalities, passive use) have increased disproportionally compared to the costs for the mitigation measures. As a result, the thresholds above which the implementation of these mitigation measures is economically beneficial have been lowered substantially.

The high passive use value of grizzly bears resulted in a very low threshold, at least when compared to collisions with large common ungulates. For example, for 3% discount rate, and for a combination of wildlife fences, a large mammal underpass once every 2 km, a large mammal overpass once every 24 km, and jump-outs, the break-even point for grizzly bear is 0.009 collisions per kilometer per year. While collisions with grizzly bears are very rare compared to collisions with common large ungulates, there are road sections where this threshold is easily reached. For example, the approximately 22 km road length between St. Ignatius and Ronan on the Flathead Indian Reservation in Montana (USA), annual grizzly bear mortality has fluctuated between 0 and 2 (Huijser et al. 2016a) and had an extreme value of 6 in 2018 (Hungry Horse News 2019). Assuming an average annual road mortality of 1 grizzly bear along this road section, it translates into 0.045 grizzly bear collisions per km per year. This is 5 times higher than the 0.009 threshold, which suggests that multiple large wildlife crossing structures (e.g. bridges and overpasses) are economically defensible based on direct road mortality for grizzly bears alone. If collisions with other large mammal species are included (e.g. white-tailed deer, black bear), extensive mitigation measures along this road section would be even more advantageous based on the economics of collisions with large wild mammal species alone.

The trend in increasing costs associated with vehicle repair costs, costs associated with human injuries and fatalities, and through including passive use values for wildlife is that we learn that the implementation of effective mitigation measures can be considered earlier and more readily than based on the cost-benefit model published in 2009.

Table 9: Threshold values for the 4 different types and combinations of mitigation measures (costs in 2020 US$).

Threshold values	Discount rate	Fence (no apron)	Fence (apron)	Fence (apron), underpass, jump-outs	Fence (apron), under- and overpass, jump-outs
US$/km/yr	1%	$6,230	$9,470	$18,499	$21,834
US$/km/yr	3%	$7,460	$11,558	$25,388	$32,030
US$/km/yr	7%	$10,496	$16,620	$43,009	$56,900
Deer/km/yr	1%	0.379	0.577	1.127	1.330
Deer/km/yr	3%	0.454	0.704	1.546	1.951
Deer/km/yr	7%	0.639	1.012	2.620	3.466
Elk/km/yr	1%	0.099	0.150	0.294	0.347
Elk/km/yr	3%	0.119	0.184	0.403	0.509
Elk/km/yr	7%	0.167	0.264	0.683	0.904
Moose/km/yr	1%	0.066	0.100	0.195	0.230
Moose/km/yr	3%	0.079	0.122	0.267	0.337
Moose/km/yr	7%	0.111	0.175	0.453	0.599
Grizzly bear/km/yr	1%	0.002	0.003	0.005	0.006
Grizzly bear/km/yr	3%	0.002	0.003	0.007	0.009
Grizzly bear/km/yr	7%	0.003	0.005	0.012	0.016

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8 APPENDIX A. VEHICLE REPAIR COST

Year	Species	Vehicle repair costs	Region	Source
2005	Deer	$2,500	USA	CNN (2006)
2006	Deer	$2,800	USA	Claims Journal (2006)
2008	Deer	$2,950	USA	State Journal-Register (2008)
2009	Deer	$3,050	USA	Auto Blog (2009)
2010	Deer	$3,103	USA	Fortune (2010)
2011	Deer	$3,171	USA	State Farm (2011)
2012	Deer	$3,305	USA	Insurance Journal (2011)
2013	Deer	$3,414	USA	Auto Guide (2013)
2014	Deer	$3,888	USA	State Farm (2015)
2015	Deer	$4,135	USA	State Farm (2016)
2016	Deer	$3,995	USA	State Farm (2017)
2017	Deer	$4,500	USA	Fender Bender (2018)
2017	Deer	$4,179	USA	State Farm (2017)
2018	Large wild ungulates	$4,341	USA	Repairer Driven News (2018)
2020	Deer	$5,510	South Dakota	DRG News (2021)
2020	Deer	$4,500	Kentucky	The Advocate-Messenger (2021)

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9 APPENDIX B. SIZE AND WEIGHT OF WILD AND DOMESTICATED LARGE MAMMAL SPECIES

Species	Height at shoulder	Length (nose to tip tail)	Weight male	Weight female	Source
Wild species					
White-tailed deer	27-45" (68-114 cm)	6'2"-7' (188-213 cm)	150-310 lbs (68-141 kg)	90-211 lbs (41-96 kg)	Whitaker (1997)
Mule deer	3'-3'5" (90-105 cm)	3'10"-7'6" (116-199 cm)	110-475 lbs (50-215 kg)	70-160 lbs (32-73 kg)	Whitaker (1997)
Elk	4'6"-5' (137-150 cm)	6'8"-9'9" (203-297 cm)	600-1089 lbs (272-494 kg)	450-650 lbs (204-295 kg)	Whitaker (1997)
Moose	6'5"-7'5' (195-225 cm)	6'9"-9'2" (206-279 cm)	900-1400 lbs (400-635 kg)	700-1100 lbs (315-500 kg)	Whitaker (1997)
Gray wolf	31”-33” (80–85 cm)	41”–63” (105-160 cm)	average 88 lbs (40 kg), range 26-175 lbs (12 - 79.4 kg)		Wikipedia (2022a)
Grizzly bear	3’4” (102 cm)	6’6” (198 cm)	180-360 kg (400–790 lbs)	290-400 lbs (130 -180 kg)	Wikipedia (2022b)
Domesticated species					
Feral horse	4'8"-5' (142-152 cm)		795-860 lbs (360-390 kg)	595-750 lbs (270-340 kg)	Whitaker (1997)
Quarter horse	4'11"-5'4" (150-163 cm)		850-1200 lbs (386-540 kg)		UHS (2007), Wikipedia (2007)
Cattle (Hereford, Angus, Shorthorn)			1,000-2,000 lbs (454-907 kg)		Wikipedia (2019)
Burro (feral donkey)	Average 4' (122 cm)		average 500 lbs (227 kg)		American wild horse campaign (2019)

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