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Cost-effective approach to reducing collisions with elk by fencing between existing highway structures

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Abstract: Collisions with large ungulates cause serious human and animal injuries and significant property damage. Therefore, wildlife crossing structures are increasingly included in new road construction to reduce wildlife–vehicle collisions, while still allowing wildlife to safely cross roads. Recently, state and federal transportation budgets have declined, concomitantly reducing the construction of wildlife crossing structures, which are generally tied to large-scale reconstruction projects that are delayed for decades into the future. Nevertheless, even during times of fiscal constraint or temporal delay, it is still necessary to reduce collisions with wildlife and maintain habitat connectivity. Therefore, it is important to find cost-effective and functional alternatives. Retrofitting roadways with wildlife exclusion fencing that directs animals to existing highway structures (e.g., sufficiently sized bridges and culverts) is a possible cost-effective, interim solution that needs further testing. Along Interstate-17 in northern Arizona, we heightened 9.17 km of right-of-way barbed wire fence to 2.4 m to guide elk (*Cervus canadensis*) to 2 large bridges and 2 modified transportation interchanges. We evaluated occurrence of elk–vehicle collisions, elk use of existing structures, and GPS movements of elk pre- and post-fencing retrofit. Post retrofit, there was a 97% reduction in elk–vehicle collisions for the 9.17 km stretch of road. There were also no increases in collisions at the fence termini (area within 1.61 km from fence ends) nor in the remaining sections, indicating that elk were not simply forced to those areas. We documented a 217% and 54% increase in elk use of the 2 large bridges, but no elk use of the transportation interchanges. GPS relocation data from 31 elk showed a statistically insignificant decrease, from 0.07 to 0.03 crossings per approach pre- and post-fence modification, respectively. Elk road crossings, determined through GPS relocations, were concentrated around the bridge structures rather than being evenly distributed across the treatment sections, and similar to collisions, crossings did not increase on adjacent fence termini. Using the Huijser et al. (2009) estimate of $17,483 for the cost to society of an elk–vehicle collision, the level of collision reduction on this stretch of road will recoup project costs in <5 years. Our results indicate that, under certain circumstances, retrofits can in the short-term reduce wildlife–vehicle collisions on roadways that are not scheduled to be reconstructed in the near future. However, for the long-term, areas with significant wildlife–vehicle collisions or habitat fragmentation should have appropriately designed, located, and maintained wildlife crossings with exclusionary funnel fencing.

Key words: *Cervus canadensis*, *Cervus elaphus*, cost-benefit, elk, existing structures, fencing, habitat connectivity, human–wildlife conflict, retrofit, ungulate, wildlife crossings, wildlife–vehicle collisions

Wildlife–vehicle collisions cause serious human and animal injuries and significant property damage (Conover et al. 1995, Groot Bruinderink and Hazebroek 1996). Wildlife crossing structures are becoming commonly used to reduce wildlife–vehicle collisions, while still allowing wildlife to access resources (Clevenger and Waltho 2000, Gagnon et al. 2011, Bissonette and Rosa 2012, Sawyer et al. 2012). Wildlife crossing structures allow wildlife to cross over or under roads where traffic volume has minimal influence versus at-grade crossings (Gagnon et al. 2007*a*, Gagnon et al. 2007*b*, Dodd and Gagnon 2011). Wildlife crossing structures combined with properly constructed and maintained wildlife exclusionary fencing, ranging in height from 2.0 to 3.0 m, appears to be most effective at reducing collisions with most large ungulates while maintaining habitat connectivity (Groot Bruinderink and Hazebroek 1996, Romin and Bissonette 1996, Clevenger and Waltho 2000, Dodd et al. 2007*a*). Clevenger et al. (2001*a*) reported an 80% reduction in ungulate mortalities along the Trans-Canada Highway in Banff National Park following exclusionary fencing linking wildlife crossing structures. Woods (1990) reported a 94 to 97% reduction in ungulate–vehicle collisions in Alberta following implementation of wildlife crossing structures and funnel fencing. Bissonette and Rosa (2012) and Sawyer et al. (2012) documented 98% and 81% reductions in mule deer (*Odocoileus hemionus*) mortalities, respectively, following installation of funnel fencing and wildlife crossing structures. Collisions with Florida Key deer (*Odocoileus virginianus claviu*) were reduced by 73 to 100% following fencing and underpass construction (Parker et al. 2008, 2011).

Figure 1: Elk (*Cervus canadensis*) would benefit from funnel fencing.

In recent years, as transportation budgets have declined, wildlife crossing structures are viewed as ancillary amenities. Additionally, while large-scale roadway reconstruction budgets can include wildlife crossing structures, those projects can take years or even decades to move through design, funding, and implementation. These fiscal and temporal constraints underscore the need for cost-effective, functional, and timely alternatives. Existing structures, such as culverts and bridges, installed during initial highway construction for water drainage, pedestrian or vehicular use could substitute as wildlife crossing structures for some species (Clevenger et al. 2001*b*, Ng et al. 2004, Grilo et al. 2008, Sparks and Gates 2012). If new construction of wildlife crossing structures is not feasible, installing wildlife exclusion fencing to connect adequately sized bridges and culverts can be a cost-effective alternative. Ward (1982) reported >90% wildlife–vehicle collision reduction of mule deer along I-80 in Wyoming with a right-of-way fence heightened to 2.4 m that directed deer to cross at structures originally intended for drainage and machinery. Researchers in Arizona documented an 85 to 97% reduction in the number of elk–(*Cervus canadensis*; Figure 1) vehicle collisions following the completion of fencing connecting wildlife crossing structures and bridges initially constructed without sufficient exclusionary fencing. Prior to fencing, elk regularly avoided the wildlife crossing structures and crossed over the highway, whereas, following fence installation, elk–vehicle collision were reduced, and use of the wildlife crossing structures increased (Dodd et al. 2007*b*, Gagnon et al. 2010). Although connecting structures with exclusionary fencing to reduce wildlife–vehicle collisions is not a new concept, there are minimal studies on the cost-effectiveness of such an approach.

With funding for wildlife–vehicle collision mitigation measures declining, it is important to determine the cost-effectiveness of wildlife crossing structures. Cost-benefit analyses can provide information on a mitigation measures' ability to reduce wildlife–vehicle collision costs (Reed et al. 1982, Huijser et al. 2009). This requires a cost to be calculated on wildlife–vehicle collisions, including deriving a value of wildlife in terms of hunter opportunity

Figure 2. Four existing structures that were connected by 9.17 km of 2.4-m-high elk retrofit exclusion fencing along Interstate-17 in northern Arizona, USA (completed in February 2012). Clockwise from top left: Munds Canyon Bridge, Schnebly Hill Traffic Interchange, Fox Ranch Traffic Interchange, and Woods Canyon Bridge.

and recreation, along with costs of emergency response, carcass removal, property damage, human injury, and fatalities (Huijser et al. 2009, Sielecki 2010). Placing a value on mitigation options seems rather straightforward; however, it needs to include design and implementation along with additional maintenance costs above and beyond what would be typically implemented (Huijser et al. 2009). Once the value of the wildlife–vehicle collisions and mitigation measures are derived, one can then determine the benefit or the difference in cost of a wildlife–vehicle collision along a given stretch of road with and without the mitigation measure in place. Ideally the benefit should equal or exceed the cost to society over the life of the mitigation measure.

The northernmost 51 km of Arizona's Interstate-17 (I-17) has a high incidence of elk–vehicle collision (Gagnon et al. 2013). In 2007, the

Table 1. Location and structural attributes of existing structures linked with retrofit fencing along 9.17 km of Interstate-17, Arizona, USA (completed in 2012). TI = traffic interchange.

Structure name	Structure type	Milepost	Width (m)[a]	Height (m)[b]	Length (m)[c]
Woods Canyon	Bridge	317.0	60.0	6.1	38.4
Fox Ranch	TI	317.9	7.9	NA	68.6
Schnebly Hill	TI	320.5	8.8	4.3	38.4
Munds Canyon Bridge	Overpass	322.0	107.6	15.2	56.7

[a] Width is the average length of northbound and southbound lanes.
[b] Height is approximate from the lowest point.
[c] Length is calculated as width of lanes plus median.

Arizona Department of Transportation worked with Arizona Game and Fish Department to gather elk movement and wildlife–vehicle collision data to incorporate wildlife crossing structures into the reconstruction plans for a 77-km stretch of I-17 (Gagnon et al. 2013). They identified 19 potential wildlife crossing structure locations for inclusion in highway reconstruction plans. Proposed wildlife crossing structures would be connected with 2.4-m-high, woven-wire fence to funnel animals to the wildlife crossing structures. However, the reconstruction was delayed, hence the need to find alternatives. Therefore, the 2 agencies focused on a 9.17-km segment that had a high incidence of elk–vehicle collision (20.3 per year, 2007 to 2010) and 4 structures with the potential to function as wildlife crossing structures (Figure 2; Table 1).

Our objectives were to evaluate the effectiveness of the heightened fencing in reducing elk–vehicle collisions, and to determine if the 2 bridges and 2 traffic interchanges functioned as wildlife crossing structures to provide connectivity for elk across I-17. We compared pre- and post-retrofit values for 3 metrics: (1) elk–vehicle collision incidences; (2) elk use of existing structures; and (3) elk movements, determined by GPS relocations. The objective of the elk–vehicle collision data analysis was to determine if the fencing changed the rates of elk–vehicle collision along the fenced section and at the fence termini. The objective of our still-camera monitoring of existing structures was to determine if structure use changed before and after fencing. The objective of our GPS data collection was to determine changes in crossing location and passage rate, or the ability of elk to get across I-17, along the fence section and fence termini. Additionally, we compared Arizona Department of Transportation project costs to elk–vehicle collision societal costs to derive the cost-benefit of the retrofit (Huijser et al. 2009).

Study area

Located entirely within Arizona, I-17 is a 235 km, 4-lane divided highway that connects Phoenix and Flagstaff. Besides local traffic, I-17 each year is travelled by millions of people who visit the Grand Canyon and other Arizona parks and recreation areas. The northernmost 51 km of I-17 immediately south of Flagstaff changes quickly in elevation and passes through both lower and higher elevation habitats, which elk utilized for summer and winter range.

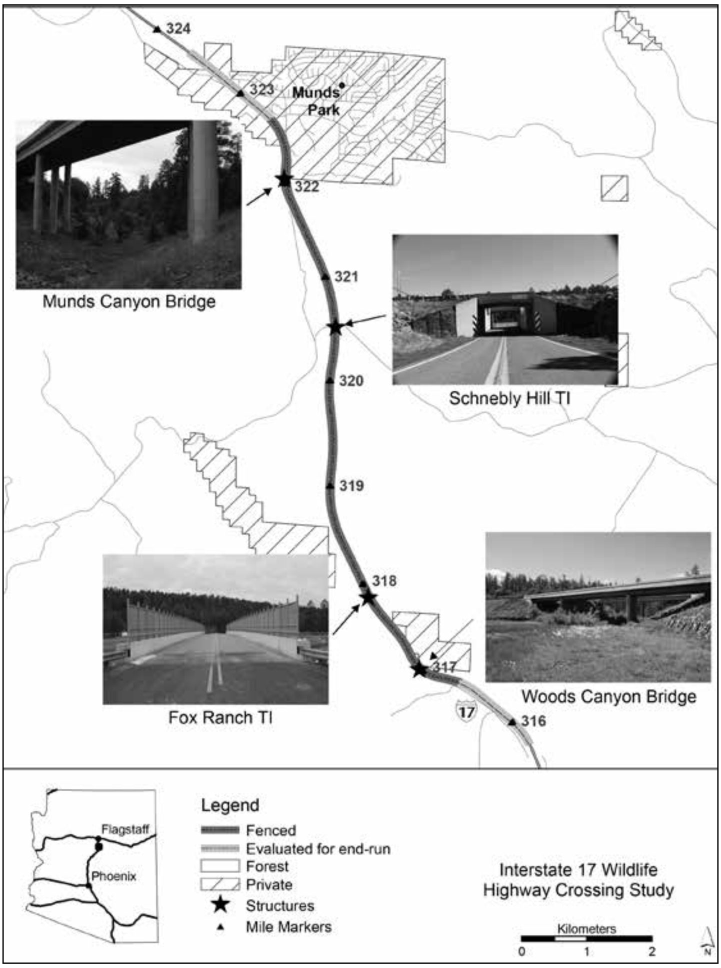

Figure 3. Map showing location of existing structures linked with 9.17 km of heightened right-of-way fence to reduce elk–vehicle collisions, and adjacent land ownership along Interstate-17 in northern Arizona, USA (completed February 2012). TI = traffic interchange.

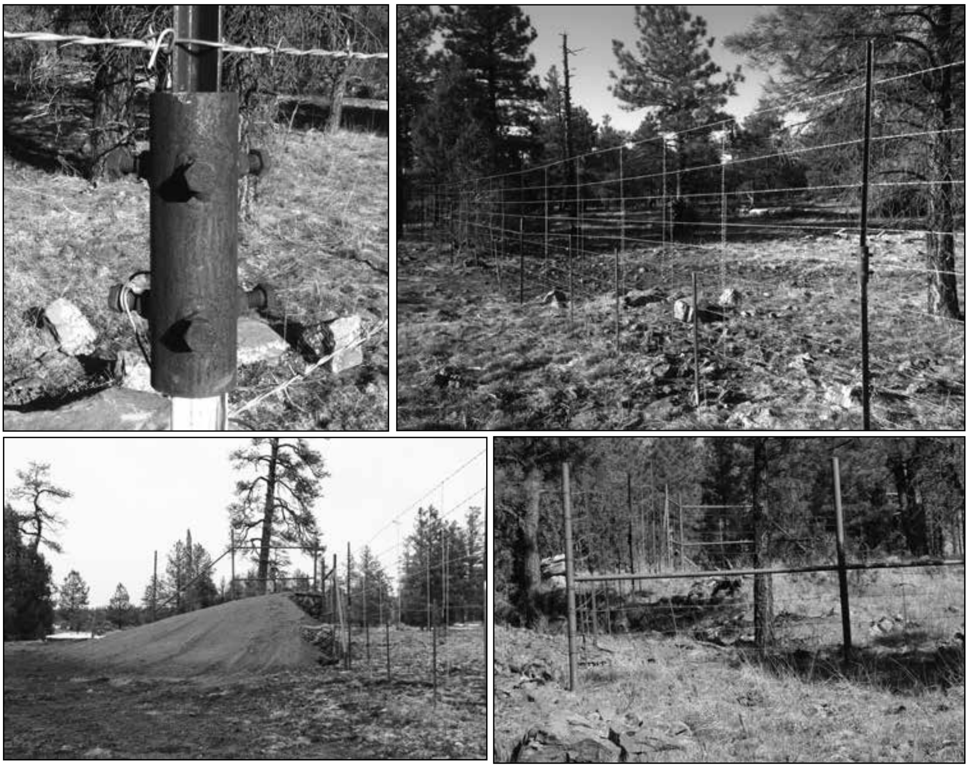

Figure 4. Example of extended existing right-of-way fence that was modified using a metal bolt on sleeve to attach a new t-post section to an existing t-post (top left). Five additional strands of barbed wire were then added to achieve a new 2.4-m-high right-of-way fence (top right). Jump-outs (bottom left) and experimental slope jumps (bottom right) were installed to allow elk trapped in the right-of-way a means of escape. This fencing configuration was used to link existing highway structures along a 9.17-km-segment of Interstate-17 in northern Arizona, USA (completed February 2012).

Migration routes parallel the highway, shifting incidence of elk–vehicle collisions spatially with migratory periods. Additionally, numerous wet meadow-riparian habitats found adjacent to or near the highway corridor and a local golf course provide a preferred food and water source influencing elk distribution and movements similar to those along nearby State Route 260 (Dodd et al. 2007*a*). Along this 51 km stretch, elk account for 75% of all wildlife–vehicle collisions and >85 elk mortalities per year (Gagnon et al. 2013). Although there is a high incidence of elk–vehicle collision along I-17, relatively few elk attempted to cross I-17, due to the highway's high traffic volumes (approximately 17,000 vehicles/day). Gagnon et al. (2013) noted a significantly low passage rate (0.09 elk crossings per approach) compared to those seen along State Route 260 (0.81 elk crossings per approach; Dodd et al. 2007*a*). Overall, elk with GPS collars crossed I-17 912 times versus nearly 11,000 times during a similar time span along State Route 260, pointing to the formidable barrier caused by I-17.

Our study area was located in a higher elevation summer range between mileposts 306 and 338 of I-17. The adjacent land is >90% managed by the U.S. Forest Service, with small private parcels. The climate is semi-arid, with hot summers, cool winters and a strong bimodal precipitation pattern. July is the warmest month, with average highs of 32^{o} C, and January the coolest, with average lows of 2.4^{o} C. Average annual precipitation is 70 cm, and average winter snowfall is 94 cm. Vegetation is Petran Montane Coniferous Forest biotic community (Brown 1994, Spence et al. 1995). Ponderosa pine (*Pinus ponderosa*) dominates the landscape. Many wet meadows are located along or adjacent to I-17, including Munds Park Golf Course, that influence elk movements (Dodd et al. 2007*a*, Gagnon et al. 2013).

Within the 51.5 km stretch of I-17, we focused primarily on 12 km (9 km of modified fenced highway and 3 km of adjacent unfenced termini). The 9 km of new exclusionary fencing incorporated Munds and Woods Canyon bridges, and Fox Ranch and Schnebly Hill traffic interchanges; Figure 3). The fencing ended just beyond the bridges allowing elk to encounter a structure to safely cross under I-17 prior to reaching the fence ends (Figure 3). Additionally, the fence ends beyond the bridges were located in areas that hindered elk movements (Gulsby et al. 2011). The north end terminated at a lighted, heavily used traffic interchange and the south end terminated at steep cliffs.

Methods

In 2012, the 9 km of 1-m, 4-wire barbed right-of-way fence was heightened to 2.4 m by using t-posts with a bolt-on extension sleeve topped with a length of t-post (Figure 4). To provide additional support, Arizona Department of Transportation installed new steel brace posts and line posts and additional stays that connected the top wires to the bottom right-of-way fence. New t-posts were installed where the right-of-way fencing was too degraded to retrofit. This heightened fencing was cheaper than woven wire and had been tested previously where elk–vehicle collision were reduced by 97% (Gagnon et al. 2010).

To help elk trapped in the right-of-way, jump-outs and experimental slope jumps were installed to permit their escape (Figure 4). Electrified mats were installed at the on- and off-ramps of Schnebly Hill and Fox Ranch traffic interchanges to block elk entrance into the right-of-way. Arizona Department of Transportation erected a fence on the parapet to eliminate wildlife jumping off the Fox Ranch traffic interchange (Figure 4, lower right).

To evaluate the effectiveness of the fencing, we used pre-fencing retrofit data from our prior research (Gagnon et al. 2013) and gathered 2 years of post-retrofit data from February 8, 2012, through February 8, 2014, using the same methodologies in both studies. Our overall objective was to compare elk–vehicle collision rates, structure use, and elk permeability across I-17 before and after fencing to determine the effectiveness of the fencing retrofit in reducing elk–vehicle collision while still maintaining connectivity for elk across I-17.

Elk–vehicle collision analysis

To document elk–vehicle collision, we compiled Department of Public Safety Collision Supplement Reports, Arizona Game and Fish Department Wildlife Vehicle Collision Reports, and Arizona Department of Transportation Report of Animal Hits into a database that documented date, time, location, species, sex, and reporting agency. For elk–vehicle collisions, pre-retrofit data was collected between January 2007 and December 2010, and post-retrofit between February 2012 and February 2014. We did not include 2011 when the fence was being constructed, because of large gaps in the fence and construction activities. For our elk–vehicle collision analysis, we evaluated the 9.17-km-fenced treatment area and fence termini sections (1.61 km, or 1 mile, beyond the fence ends). Our objectives of the elk–vehicle collision analysis were to evaluate changes in elk–vehicle collision or existence of an "end run" following fencing (Bellis and Graves 1971, Ward 1982, Clevenger et al. 2001*b*, McCollister and van Manen 2010, Bissonette and Rosa 2012). We also evaluated elk–vehicle collisions in the remaining 39 km (16 km south and 23 km north of the study area, respectively) of high elk–vehicle collision to determine if elk–vehicle collision were simply shifted to other areas.

Elk-use of existing structures

To determine the frequency that elk used structures, we installed Reconyx® Professional Model single-frame cameras. Each bridge required multiple cameras to photograph the crossing area. To minimize vandalism, we mounted cameras roughly 3.6 m high. Given the large expanses of the bridges, we were not able to accurately record the ratio of crossings to approaches (Reed et al. 1975, Dodd et al. 2007*a*, Cramer 2013). Given the reasonable assumption that species distributions remained constant, we assumed that direct crossing rates were an acceptable measure of bridge utilization before and after fencing. To document wildlife use of structures, we collected 19 months of camera data prior to and during fence construction, and 19 months of post-retrofit data. We had no pre-data for the traffic interchange's, but following the fencing retrofit, we installed 1 camera at each traffic interchange to monitor wildlife

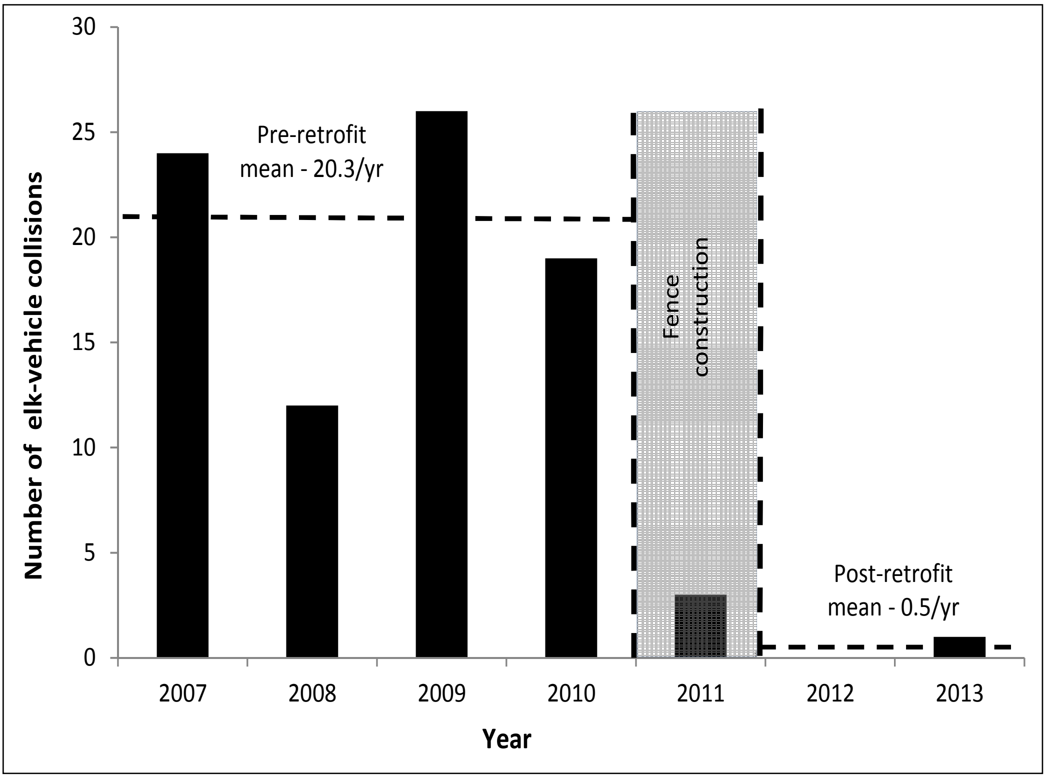

Figure 5. Total number (black bars) and mean (dashed line) elk–vehicle collisions by year, before and after a fencing retrofit to exclude elk from a 9.17-km section of Interstate-17 in Arizona, USA, 2007 to 2013.

use from February 2012 to February 2014. Our objective of the still camera data collection was to determine changes of use over time, before and after fencing.

Elk GPS movement data

To determine if elk movements relative to the installation of fencing changed, we compared the portion of the pre-GPS telemetry (2007 to 2010) data that fell within the limits of the fencing and termini segments to the post-retrofit (February 2012 to February 2014) GPS telemetry data. For the post-retrofit data, we captured elk in modified Clover traps (Clover 1954) baited with salt and alfalfa hay adjacent to the retrofitted portion of I-17 and fence termini. We utilized the portion of trap sites located in these areas established during the 2007 to 2010 capture efforts (Gagnon et al. 2013). We fitted elk with a combination of Telonics Inc. Model TG3 and Model TG4 store-on-board and Model SST-TG3 Spread Spectrum GPS collars programmed to receive 8 relocations per day between 1700 to 0700 hours for approximately 2 years. We used ArcGIS Version 10 Geographic Information System (GIS) software (ESRI, Redlands, Calif.) for our GPS data analysis. To evaluate changes in permeability of the highway by elk, we calculated a mean passage rate, or the ratio of crossings to approaches, for elk in the treatment section and fence termini (Dodd et al. 2007*c*, Gagnon et al. 2007*a*). Crossings were defined as 2 consecutive GPS relocations on each side of the road within a 2-hour period. Approaches are calculated as the number of GPS relocations that fall within 250 m of the highway. We used Mann-Whitney *U* tests (Sokal and Rohlf 2003) to test the null hypothesis that no differences occurred between number of crossings, number of approaches, and passage rates. To determine changes in crossing distribution we compared the proportion of all crossings associated with the treatment area, existing structures, and fence termini. Our objective for collecting GPS data was to determine changes in crossing location and passage rate, or the ability of elk to get across I-17 along the fence section and fence termini.

Table 2. Frequency of elk-vehicle collisions per year (elk–vehicle collision/yr) collected by Arizona Game and Fish Department, Arizona Department of Transportation, and Department of Public Safety before and after fencing modifications to exclude elk along a 9.17 km section of highway, the adjacent 1.61 km sections, and the surrounding 39.1 km of remaining high elk–vehicle collision sections of Interstate-17, Arizona, USA, 2007-2013.

Year*	Fenced Sections (9.17 km) Elk–vehicle collision/yr	Fence Termini (3.22 km) Elk–vehicle collision/yr	Remaining Sections (39.10 km) Elk–vehicle collision/yr
	Before fencing retrofit		
2007	24	3	68
2008	12	6	79
2009	26	3	62
2010	19	6	40
Mean	20.3	4.5	62.3
	After fencing retrofit		
2012	0	3	64
2013	1	1	54
Mean	0.50	2	59

*2011 transition year (fence construction) left out of this analysis.

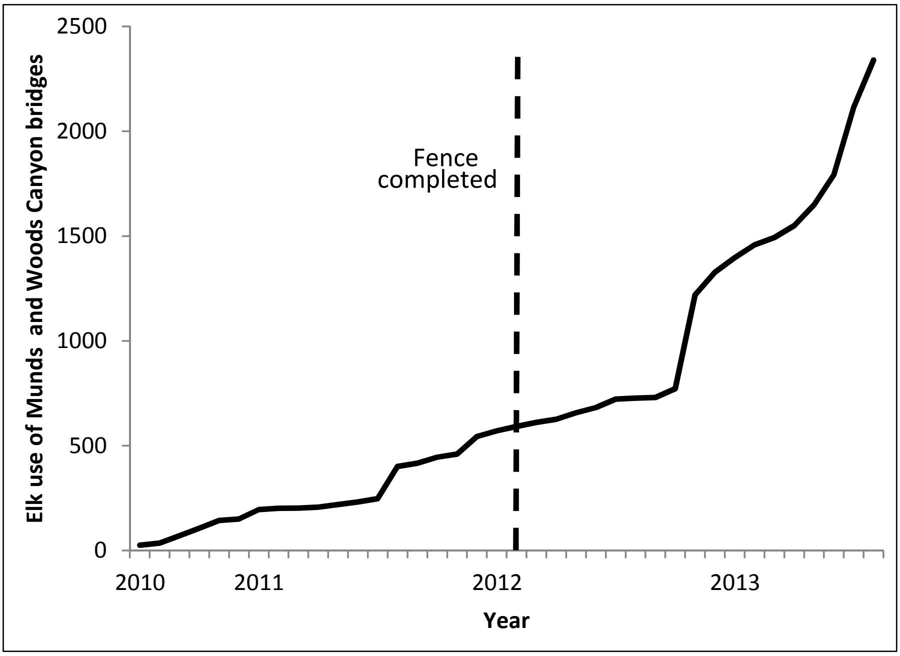

Figure 6. Cumulative number of elk crossing under Munds and Woods Canyon Bridges before (19 months) and aft er (19 months) a fencing retrofit to exclude elk from a 9.17 km section of Interstate-17 and connect existing structures from July 2010- August 2013, Arizona, USA.

Table 3. Number of wildlife crossings at Munds and Woods Canyon Bridges, Interstate-17, Arizona, USA, July 2010–August 2013.

Number of crossings	Elk	Deer	Meso-carnivores	Large carnivores	Other	All
Munds Canyon Bridge	2,270	358	224	4	58	2,914
Woods Canyon Bridge	70	77	45	0	34	226
Total	2,340	435	269	4	92	3,140

Table 4. Comparison of elk highway crossings, approaches, and passage rates along Interstate-17 before and after modification of a 9.17 km section of right-of-way fencing to exclude elk and connect existing highway structures, and the 3.22 km of fence termini from 2007-2014.

	Parameter	Mean (±SE)		Mann-Whitney *U*-test comparison of means
		Before retrofit fencing (SE)	After retrofit fencing (SE)	
Treatment section	No. highway crossings/elk	4.30 (1.12)	2.38 (1.01)	$U = 397$ $P = 0.22$
	Highway approaches/elk	67.61 (11.53)	82.72 (9.59)	$U = 597$, $P = 0.22$
	passage rate (crossings/approach)	0.07 (0.02)	0.03 (0.01)	$U = 405$, $P = 0.27$
Termini sections	No. highway crossings/elk	0.55 (0.29)	0.33 (0.22)	$U = 115$, $P = 0.80$
	Highway approaches/elk	26.10 (4.63)	26.0 (4.54)	$U = 126$, $P = 0.83$
	passage rate (crossings/approach)	0.03 (0.02)	0.01 (0.01)	$U = 114$, $P = 0.75$

Cost versus benefit

To evaluate the cost-effectiveness of the treatment, we compared the 2007 to 2010 pre-retrofit costs (Huijser et al. 2009) of accidents to the costs of the reduced elk–vehicle collision post-retrofit (2012 to 2014) . We projected these annual values to determine when the benefit realized by the treatment would exceed its cost.

Results

Elk-vehicle collision analysis

Prior to retrofit fencing (January 2007 to December 2010), we documented 20.3 elk–vehicle collision per year in the section of highway that would ultimately be fenced (Figure 5). During 2 years post-retrofit (February 2012 to February 2014), we documented 1 elk–vehicle collision (0.5 elk–vehicle collision per year), a 97% reduction in elk–vehicle collision in this same area (Table 2; Figure 5). We found an elk–vehicle collision reduction of 55% within the adjacent fence termini segments (Table 2). In the remaining areas of high elk–vehicle collision we documented a nominal 6% reduction in elk–vehicle collision following fencing, indicating that elk–vehicle collision were not simply forced to other areas (Table 2). We noted a decrease in deer–vehicle collisions from 3.0 per year pre-retrofit to 1.5 collisions post-retrofit, even though the type of retrofit fencing Arizona Department of Transportation used did not restrict deer as well as it did elk. We documented 8 additional wildlife–vehicle collisions within the retrofit section (6 mule deer and 2 black bears [*Ursus americanus*]).

Elk use of existing structures

During 38 months (19 months pre- and post-retrofit), our cameras detected bridge crossings by 14 species consisting of 3,140 animals, of which 2,340 were elk (Table 3). Bridge use by nontarget species included: 437 ungulates (416 mule deer, 19 white-tailed deer, 2 collared peccary [*Tayassu tajacu*]); 270 mesocarnivores (21 bobcats [*Lynx rufus*], 13 coyotes [*Canis latrans*], 41 gray foxes [*Urocyon cinereoargenteus*], 188 raccoons [*Procyon lotor*], 6 skunks [*Mephitis* spp.], and 1 ringtail cat [*Bassariscus astutus*]); and 4 large carnivores (3 mountain lions [*Puma*

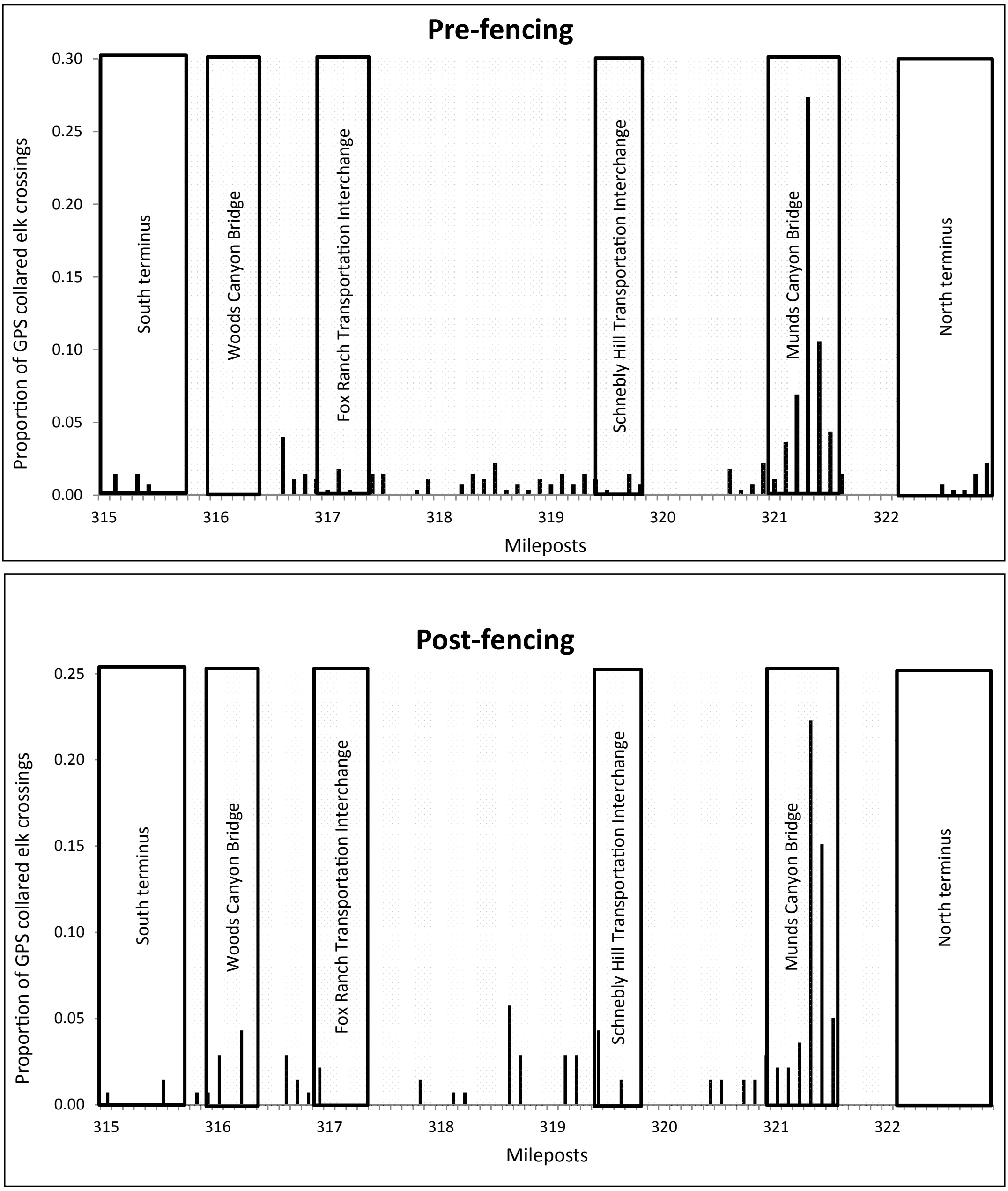

Figure 7. Proportion of elk crossings determined through GPS-collar data collected in 2-hour intervals along a 12.39 km (9.17-k-fencing retrofit, 1.61 km beyond each fence terminus) stretch of Interstate 17 before (2007–2010; top graph) and after (2012–2013; bottom graph) a fencing retrofit to exclude elk and location of existing structures from 2010–2014, Arizona, USA. Light grey shading indicates the fenced retrofit section. Black-outlined rectangles depict class bins attributed to existing structures and fence end sections.

concolor] and 1 black bear). Other wildlife species included 94 rock squirrels (*Spermophilis variegatus*), 5 mallards (*Anas platyrhynchos*), and a great blue heron (*Ardea herodias*). Animals not included in our tally were 79 cattle, 8 house cats, 34 domestic dogs, and 6 unidentified animals.

At Munds Canyon and Woods Canyon bridges, we documented an increase in elk crossings following installation of the retrofit fencing (Figure 6). At Munds Canyon Bridge, the larger of the bridges, we documented 545 elk crossings pre-fencing and 1,725 elk crossings post- fencing, a 217% increase. At Woods Canyon Bridge, we documented 26 elk crossings pre- and 44 crossings post-retrofit or a 54% increase.

Incidentally, although deer were not our focal species, we documented a 69% (*n* = 352) and 350% (*n* = 77) increase in deer-use of Munds and Woods Canyon bridges, respectively. Following retrofit completion, we documented no ungulate crossing the traffic interchange structures, although 1 raccoon and 1 coyote crossed.

Elk GPS movement data

Where the fence would be heightened pre-retrofit, 33 elk approached the highway, a mean of 67.6 (±11.5 = SE) approaches; they crossed the highway a mean of 4.3 (±1.1) times (Gagnon et al. 2013). Post-retrofit, 31 elk approached the highway 82.7 (±9.6) times, and crossed the highway 2.4 (+1.0) times per elk. The mean passage rate for all elk along this section prior to fencing was 0.07 (±0.02) crossings per approach. Post-retrofit, mean passage rate on the retrofit section was reduced to 0.03 (±0.01) crossings per approach. This represents a 57% reduction in passage rate relative to the already low pre-retrofit mean (Table 4). A similar comparison of pre- and post-retrofit passage rates within the fence termini sections showed a 53% reduction from 0.03 (±0.02) to 0.01 (±0.01) crossings per approach (Table 4).

We noted a subtle shift in the distribution of GPS-collared elk highway crossings to the bridges between pre- and post-retrofit treatments (Figure 7). The highest peak was at Munds Canyon Bridge, with another smaller peak at the Woods Canyon Bridge. In the total treatment section between the bridges, the proportion of crossings prior to treatment (0.32) did not differ substantially following the retrofit (0.38). The 2 traffic interchanges lacked crossings before and after fencing. No significant peaks in elk crossing distributions occurred at fence termini (Figure 7).

Cost versus benefit

Huijser et al. (2009) calculated the mean cost to society of an elk–vehicle collision to be $17,483. Pre-retrofit, the annual mean along our treatment section (20.3 elk–vehicle collision), had a cost of $354,905 per year. In the first 2 years following the fence retrofit, we documented a single elk–vehicle collision, with a cost of $8,742. Hence, the 97% decrease in elk–vehicle collision represented an economic benefit of $346,163 per year. The cost of the fencing project was $1.66 million; hence, if all remains constant, the project will pay for itself in <5 years. Additionally, numbers of serious human injuries and even death could be avoided.

Discussion

Retrofitted exclusion fencing linking existing structures reduced elk–vehicle collision by 97%. Elk use of existing structures increased following fencing, indicating that some level of connectivity was maintained. Although passage rate was reduced, GPS movement data showed no statistically significant change in the ability of elk to cross the already substantial barrier posed by I-17 that was documented by Gagnon et al. (2013). Neither elk crossings nor elk–vehicle collision rates increased at the fence termini, suggesting that elk movement patterns did not result in an "end run effect." These results indicate that retrofit fencing connecting existing structures reduced elk–vehicle collision, while still allowing elk to cross the road and not forcing them to cross in other areas. The benefit realized through reduced elk–vehicle collisions would exceed the cost in <5 years. Although this project reduced elk–vehicle collisions, while still allowing elk to cross I-17 at a relatively low cost, several caveats need to be considered before using this type of fencing to connect potential crossing structures on other highways.

Although we showed a significant reduction in elk–vehicle collisions using this type of fence, on multiple occasions we still documented elk tracks in the right-of-way. In some instances, elk pushed their way between the wires. The fencing for this project was not 2.4 m woven-wire fencing commonly used to exclude animals from roadways. Rather, it was a heightened barbed-wire fence. Our reasons for using this fence were its lower costs and to exclude elk without hindering smaller species' movements (Gagnon et al. 2010). It was important not to hinder movements of other smaller wildlife, given that structures were not spaced appropriately for most wildlife species (Bissonette and Adair 2008). We believe that the reduction in elk–vehicle collisions, in spite of the elk access through the right-of-way fence, is a combination of the barrier effect caused by traffic volume and insufficient incentive

(Gagnon et al. 2007*a*). Incentives that would potentially cause more elk to push through the heightened right-of-way fencing could include: vegetation within the right-of-way, making it substantially preferable to the surrounding habitat (Bellis and Graves 1971, Puglisi et al. 1974); juxtaposition to preferred resources (e.g., riparian meadows, agriculture) in relation to elk movement patterns (Dodd et al. 2007*a*); and newly fenced roads that intersect migratory paths (Sawyer et al. 2012). In cases where these motivations to cross roads exceed the deterrent of the barrier effect of the highway, 2.4 m woven-wire fence should be used to connect wildlife crossing structures (Clevenger and Waltho 2000, Gagnon et al. 2011, Bissonette and Rosa 2012, Sawyer et al. 2012).

Regular fence maintenance, even of woven wire, is essential for a continued reduction in wildlife–vehicle collisions. Although we noted a 97% reduction during our 2-year study, we continued to work with Arizona Department of Transportation and the Department of Public Safety and documented 4 elk killed within the fenced area in 2014, as a result of compromised fence integrity. Erosion and cuts in the fence were responsible for 3 elk mortalities, and the entry point of the remaining elk mortality was unknown, but it was in close proximity to one of the electrified mat wildlife guards. Regular inspections and immediate repairs to fences are important, because breaches can quickly lead to concentrated collision zones from animals following the fence to the first opening they encounter.

Appropriate siting of fence termini is also needed to minimize "end runs" (Bellis and Graves 1971, Clevenger et al. 2001*b*, McCollister and van Manen 2010, Gulsby et al. 2011). Additionally, intermittent exclusionary fencing with no crossing structures can cause multiple end runs (McCollister and van Manen 2010). We did not detect an increase in elk–vehicle collisions at the fence ends, suggesting that it was appropriate to locate the ends within a short distance of suitable existing (or newly built) structures and into areas immediately beyond the structures that elk would otherwise avoid.

As an alternative to locating termini at structures or specific avoidance areas, fencing can be extended well beyond wildlife–vehicle collision areas. Bissonette and Rosa (2012) noted no increased collisions at fence termini, which was attributable to extending fences beyond collision hotspots. Ward (1982) noted that deer–vehicle collisions occurred at the end of newly constructed ungulate-proof fence in Wyoming that was fixed by constructing an additional 1.61 km of fencing. In all of these cases, including our own, the success of the exclusion fencing hinged on the presence of wildlife crossing structures or existing structures within the fenced area. Fencing without crossing structures is less effective at excluding wildlife from the road (Bellis and Graves 1978, Falk et al. 1978, Feldhamer et al. 1986).

Along the northern 51.5 km of I-17, elk passage rates, prior to retrofit exclusion fencing, were an already low 0.09 crossings per approach for the overall highway corridor and 0.07 crossings per approach for the area that would ultimately be fenced (Gagnon et al. 2013). Low passage rates prior to fencing indicate an impediment caused by high traffic volume. Seiler (2003) suggests that roads exceeding 10,000 vehicles per day become effective barriers to wildlife. Average annual daily traffic volumes that exceeded 16,000 vehicles per day likely become a "moving fence" (Bellis and Graves 1978). It appears that there is a threshold for elk to risk crossing high-traffic highways, such as I-17 (Gagnon et al. 2007*a*, Gagnon et al. 2013). Elk along I-17 were able to overcome high-volume traffic by crossing not only at large bridges but also at areas where lanes were separated by medians nearly 1-km wide versus "bundled" lanes (Jaeger et al. 2006, Gagnon et al. 2013). At these large medians, elk essentially cross 2 separate highways with lower traffic volumes. As a comparison, elk had a passage rate of 0.81 crossings per approach along State Route 260 with approximately 8,000 average annual daily traffic volumes (Gagnon et al. 2007*a*, Dodd et al. 2012*a*).

Elk along I-17 appear to show higher road avoidance than elk along other highways in Arizona (Dodd et al. 2012*a*, Dodd et al. 2012*b*, Gagnon et al. 2013); however, the animals that do attempt to cross face a high probability of mortality. Gagnon et al. (2013) noted that though frequent crossers accounted for 8.4% of the collared elk, they accounted for 60% of the elk–vehicle collisions involving collared elk along I-17. With the increase in use of Munds and Woods Canyon bridges, we documented that those elk that were directed to the existing structures by the exclusionary fencing still crossed I-17.

Besides adequate fencing, retrofitting requires that structures need to be properly located and of sufficient size. Smaller structures can reduce the ability of wildlife to cross roads even if they are linked with funnel fencing, as they did in our case where the 2 traffic interchanges did not pass elk. Even Woods Canyon Bridge, a relatively large structure that showed a 54% increase in elk crossings from 26 to 44 elk, was inferior to the larger Munds Canyon Bridge where 1,725 elk crossed after completion of the retrofit. In previous studies, elk were initially reluctant to use even larger, more open structures, but over time they learned to use them (Dodd et al. 2007*d*, Gagnon et al. 2011). Given that elk adapt to using structures, use of Woods Canyon Bridge will likely increase (Clevenger and Waltho 2003, Gagnon et al. 2011). This does not imply that elk will use all structures over time as elk have a lower tolerance for smaller structures than mule deer or white-tailed deer (Gagnon et al. 2011, Sparks and Gates 2012, Cramer 2013). However, even more accepting species, such as deer, have thresholds that they are unwilling to cross (Reed 1981, Gordon and Anderson 2003, Sparks and Gates 2012, Cramer 2013). This reluctance leads to animals jumping, forcing their way through, using gaps under the fence, or traversing the road at the end of the fence. Migratory animals can be confined to areas where they cannot survive year-round or where habitat fragmentation can be exacerbated. Thus, before installing retrofit fencing, consideration should be given to fit the size and design of the structures to the species. Motorist safety, of course, also is to be considered when planning a retrofit. We knew that the 2 bridges had some level of elk use, while the fencing would reduce the high levels of elk–vehicle collision to some level. We did not know if the elk would use the traffic interchanges and if they did not use the traffic interchange's during the time of this study.

Huijser et al. (2009) calculated that a pre-mitigation level of 1.2 elk–vehicle collisions/km/year is the break-even point to justify new wildlife underpasses and woven-wire wildlife fencing with jump-outs assuming an 86% reduction in ungulate-vehicle collisions over 75 years. That is, a reduction of 1 elk–vehicle collision/km/year over 75 years will justify the cost of new underpasses and fencing for a stretch of road. Our treatment area exhibited 2.21 elk–vehicle collision/km/year—almost twice the level that justifies new wildlife underpasses and fencing. In our study, there was no cost for the construction of underpasses, because we utilized already in-place bridges, adding to the cost-effectiveness of retrofits versus requiring newly constructed wildlife crossing structures with funnel-fencing. Our estimate does not include deer–vehicle collisions, since deer can still access the road with the fencing we used. However, given the reduction in deer–vehicle collisions, even by using heightened barbed wire fencing, the benefit of the retrofit exceeded further the cost derived from calculating elk–vehicle collision reduction alone.

Maintenance for the heightened barbed wire fence will eventually exceed that of a woven-wire fence. Maintenance costs are assumed constant in the near-term; however, longer-term costs are likely to increase, because the fence is weaker than woven wire. Huijser et al. (2009) included maintenance and fence replacement costs every 25 years that matched a crossing structure life of 75 years. Although, these long-term costs will eventually be incurred to alleviate elk–vehicle collision along I-17, the fact that the benefit of the heightened right-of-way fencing we used will exceed its cost in <5 years points to its value as a retrofit measure to reduce motorist injuries and property damage while maintaining wildlife connectivity.

Eventually, we will need to transition to properly designed wildlife crossing structures and standard woven-wire, ungulate-proof fencing. Until that happens, we demonstrated that there is a cost-effective alternative that can be used in some places to increase both motorist and wildlife safety until longer-term, more permanent solutions can be constructed.

Management implications

Fencing alone or when combined with inadequately sized and spaced passage structures, can have a lasting impact on wildlife by blocking movements to important seasonal ranges. However, under the right circumstances, retrofitting existing structures that are adequately sized to pass the target species with exclusion fencing is a cost-effective measure that reduces wildlife–vehicle collisions, while maintaining habitat connectivity until properly designed, located, and maintained wildlife crossing structures and fencing can be constructed.

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