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Enhancing existing isolated underpasses with fencing reduces wildlife crashes and connects habitat

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Abstract: The impact of wildlife–vehicle collisions on drivers and wildlife populations has been gaining attention in the United States. Given the established success of wildlife crossings with fencing in reducing wildlife crashes and connecting habitat, information is needed on cost-effective means of implementation for departments of transportation. When wildlife crossings are constructed, they are often built into new road projects as a series of 2 or more underpasses and/or overpass structures connected by exclusionary fencing. Given limited transportation budgets and the prevalence of maintenance activities more so than new construction in many states, enhancing existing underpasses on previously constructed roads has been recognized as a cost-effective mitigation opportunity. More research is needed, however, on the effects of adding fencing to existing underpasses, particularly those that are too far from one another to be connected with contiguous fencing. In this study, we evaluated the effectiveness of this measure when applied to isolated underpasses. Approximately 1.6 km of 2.4-m-high wildlife fencing was added to each of 2 existing underpasses, a large bridge underpass and a large box culvert, situated approximately 8 km apart from one another on Interstate 64 in Virginia, USA. We conducted a 2-year post-fencing camera monitoring study and compared the findings from a 2-year pre-fencing study with regard to collision frequencies with white-tailed deer (*Odocoileus virginianus*) and black bears (*Ursus americanus*); the use of the underpasses by wildlife; and roadside deer activity. We also evaluated deer activity data to compare different fence end designs applied at the study sites. After fencing installation, deer–vehicle collisions (DVCs) were reduced by 96.5% and 88% at the box culvert and bridge underpass, respectively, and there were no increases in DVCs within 1.6 km of the fence ends. Deer crossings increased 410% at the box culvert and 71% at the bridge underpass. Use of the culvert and bridge underpasses by other mammals increased 81% and 165%, respectively. Although deer use of the underpasses was much greater than their activity at any of the fence ends, there was relatively high deer activity at the fence ends that did not tie into a feature such as right-of-way fencing. Our study found that the addition of wildlife fencing to certain existing isolated underpasses can be a highly cost-effective means of increasing driver safety and enhancing habitat connectivity for wildlife. The benefits from crash reduction exceeded the fencing costs in 1.8 years, and fencing resulted in an average saving of >$2.3 million per site over the 25-year lifetime of the fencing. The results add to the growing body of knowledge about effective ways we can use existing infrastructure to connect wildlife habitat and increase driver safety.

Key words: deer–vehicle collisions, fence end, *Odocoileus virginianus*, *Ursus americanus*, Virginia, wildlife crash mitigation, wildlife crossings, wildlife fencing, wildlife underpasses, wildlife–vehicle collisions

The impact of wildlife–vehicle collisions on drivers and wildlife populations has been receiving increased attention in the United States in recent decades (Vartan 2016, Schaffer 2019, Fisher 2020). Because driver safety is a priority to departments of transportation (DOTs), mitigation efforts often focus on reducing collisions with large hooved mammals such as deer (*Odocoileus* spp.). Recent auto insurance industry annual estimates indicate that U.S. motorists have a 1 in 116 chance of colliding with a deer, elk (*Cervus canadensis*), or moose (*Alces alces*; State Farm 2020). Given their high frequency, deer–vehicle collisions (DVCs) are estimated to be among the costliest collision types in Virginia, USA, averaging >$533 million per year (Donaldson 2017).

The success of wildlife crossings (overpasses or underpasses) with fencing has been well established in recent decades (Dodd et al. 2007, Gagnon et al. 2010, Clevenger and Huijser 2011, Kintsch et al. 2020), resulting in an increase in their construction in the United States (Vartan 2016). The reduction in vehicle collisions with deer and elk as a result of these measures is typically >80% (Clevenger et al. 2001, Sawyer et al. 2012) and was 90% or more in several studies (Woods 1990, Parker et al. 2011, Bissonette and Rosa 2012, Kintsch et al. 2020). Wildlife crossings also increase highway permeability and promote genetic connectivity. Highly mobile species such as deer can be particularly sensitive to the effects of highway impermeability (Klar et al. 2009, Robinson et al. 2012, Rytwinski and Fahrig 2012). A large-scale genetic study of white-tailed deer (*O. virginianus*) in Wisconsin, USA found significant barrier effects of the highway system, which can have consequences with regard to population overabundance and disease spread (Robinson et al. 2012).

Support for the increase of efforts to identify wildlife corridors and construct wildlife crossings is reflected in a series of wildlife corridor legislation passed in the United States in recent years, some of which direct the DOT to construct wildlife crossings in areas with a high risk of wildlife crashes and/or where roads transect identified wildlife corridors (Fisher 2020). The recognized need for wildlife to travel in response to climate change is further bolstering these efforts (Senate Environment and Public Works Committee 2019, Guarino 2020).

Given the success of wildlife crossings and the associated increased demand for these measures, research is needed on cost-effective means of implementation for DOTs. Wildlife crossings are typically constructed as a series of 2 or more underpass and/or overpass structures connected by exclusionary fencing (Clevenger et al. 2001, Forman et al. 2003, Dodd et al. 2007, Huijser et al. 2009, Gagnon et al. 2010). Although the costs for these structures can represent a relatively small portion of the overall project budget when incorporated into a new road project, it can be a challenge for DOTs to allocate sufficient funds for these features on roads that have already been constructed. For these roads, a cost-effective mitigation opportunity is to enhance existing underpasses that were not designed for wildlife but may be used by them to cross beneath the road. Although published research is limited, studies in the southwestern United States have shown that the addition of fencing to connect existing underpasses used by wildlife (regardless of whether the underpasses were designed for wildlife) is an effective means of crash reduction (Ward 1982, Dodd et al. 2007). Elk–vehicle collisions were reduced by 85–97% in Arizona, USA after fencing was constructed to connect wildlife crossing structures (Dodd et al. 2007, Gagnon et al. 2010). Similarly, elk–vehicle collisions decreased 97% after the height of 0.9-m fencing was increased to 2.4 m between 2 large bridges and interchanges along Arizona's Highway 17; the use of these bridges by elk increased by 217% and 54% (Gagnon et al. 2015).

Opportunities to connect habitat and reduce wildlife crashes by enhancing existing underpasses with fencing are plentiful in the United States (Forman et al. 2003), but there is little research on the effects of adding fencing to structures that are isolated (i.e., too far from another underpass to be connected with contiguous fencing). Connecting distant existing underpasses that may be viable for wildlife passage can be detrimental to some species. The longer the exclusionary fencing, the less likely it is that all animals can reach the underpass (McCollister and Van Manen 2010). Without an accessible underpass, fencing can adversely affect populations that need access to resources on both sides of the road (Jaeger and Fahrig 2003). Understanding the effectiveness of adding discrete sections of fencing to isolated structures (rather than connecting 2 or more distant structures) is therefore needed, particularly if such measures are to be implemented on a larger scale.

For this approach, the design of the ends of a fence is of particular importance to minimize "end runs," whereby an animal circumvents the fencing by traveling from the habitat side of the fence end to the roadside. Clevenger et al. (2001) found an increase in ungulate–vehicle collisions within 1 km of fence ends, although the authors concluded that major drainages near the fence ends likely influenced these occurrences. Conversely, Bissonette and Rosa (2012) and Gagnon et al. (2015) found no increases in wildlife–vehicle collisions at fence ends. The risk of end runs can be minimized by tying the fence ends into areas of steep topography or other obstacles that create difficulty for the animal to circumvent the fence end (Huijser et al. 2015, Jared et al. 2017).

Our primary objective for the study was to determine the effectiveness of enhancing existing isolated underpasses with wildlife fencing.

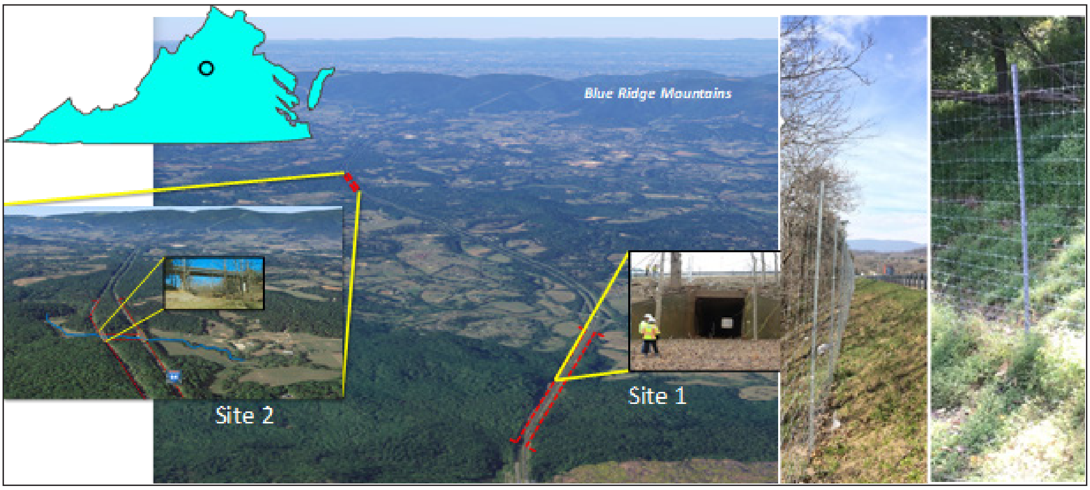

Figure 1. Study area illustrating underpasses, locations of fencing (dashed red lines), and photographs of fencing along the roadside (right), Interstate 64, Virginia, USA.

Neither of the underpasses evaluated were designed to accommodate vehicular traffic. We determined effectiveness by conducting a 2-year post-fencing study and comparing the findings from a 2-year pre-fencing study at the same locations (Donaldson et al. 2016). Both studies used cameras to quantify wildlife activity at the underpasses and the adjacent roadside before and after fencing construction. We compared pre- and post-fencing findings with regard to whether the fencing changed (1) the frequency of DVCs, (2) the use of the underpasses by deer and other wildlife, and (3) deer activity levels along the roadside, including at the fence end areas.

We also used deer behavior and activity data to make comparisons among the different fence end designs applied at the study sites. Finally, we conducted a cost analysis to compare the costs of the fencing with the savings from any DVC reductions at the study sites.

In the subsequent sections, we use "DVCs" to indicate data collected from deer carcass removal records. Deer-related vehicle collisions from police records are referred to as "police-reported DVCs."

Study area

The study sites were along Interstate 64 in Virginia, approximately 16 km and 24 km east of the Blue Ridge Mountains and several kilometers west of the city of Charlottesville. The interstate at the study sites is a 4-lane highway surrounded by oak-hickory forest interspersed with patches of agricultural land.

Annual average daily traffic on Interstate 64 ranges between 27,000 and 49,000. Deer carcass removal records indicated that DVCs were the most frequent type of collision in this area compared to all police-reported crash types (Donaldson et al. 2016). Vehicle collisions with black bears (*Ursus americanus*) are also frequently reported in this area, as the nearby mountains intersected by the interstate serve as important habitat for bears and other wildlife. Other common terrestrial wildlife that inhabit the area include the Virginia opossum (*Didelphis virginiana*), raccoon (*Procyon lotor*), red fox (*Vulpes vulpes*), gray fox (*Urocyon cinereoargenteus*), bobcat (*Lynx rufus*), coyote (*Canis latrans*), striped skunk (*Mephitis mephitis*), and groundhog (*Marmota monax*).

A previous camera monitoring study in the study area found frequent use of the interstate roadside by deer, where their predominant behaviors along the roadside were feeding and walking parallel to the interstate (presumably searching for areas to cross; Donaldson et al. 2016). Although the proportion of deer that attempted to cross the highway was found to be relatively low compared the proportion of deer using the roadside for feeding, these crossing attempts resulted in a large number of DVCs. Deer carcass removal records indicated that the number of DVCs was up to 8.5 times greater than those in police reports and DVCs were the most frequent type of collision compared to other reported crash types (Donaldson et al. 2016).

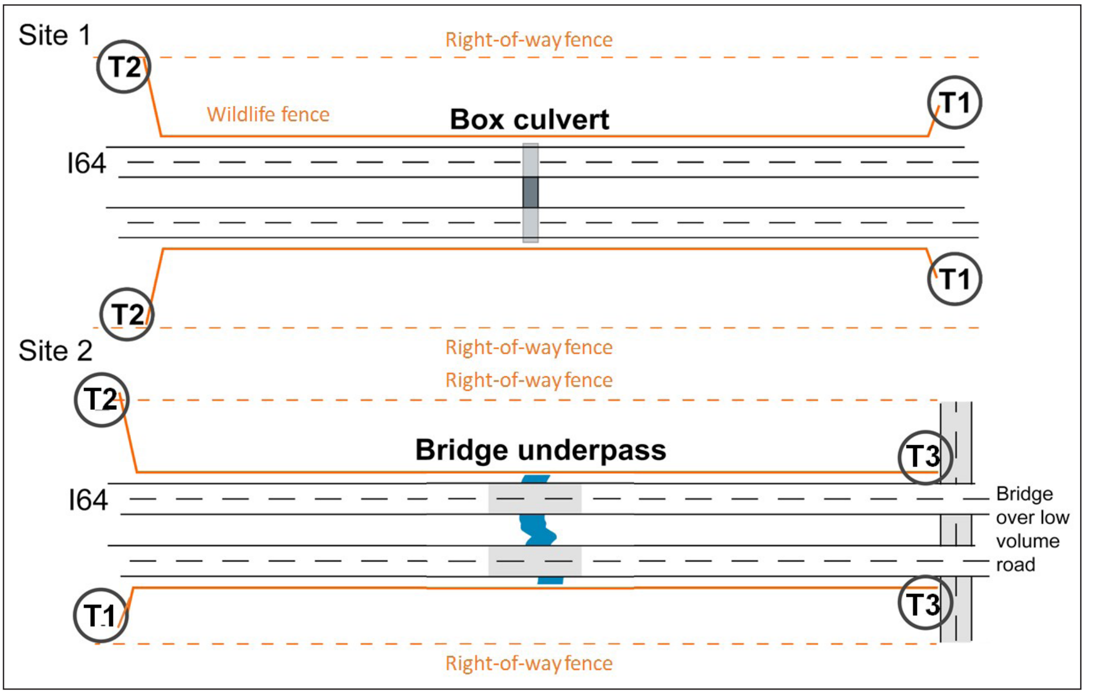

Figure 2. Fence end treatments at the 2 study sites, Interstate 64, Virginia USA (2017–2019). Treatment 1 (T1) = fence end angles away from road and does not tie into any structure or landscape feature. Treatment 2 (T2) = fence end angles away from road and ties in with 1.2-m-high right-of-way fencing. Treatment 3 (T3) = fence end ties in with a bridge underpass.

Methods

Wildlife fencing design and construction

The underpass at site 1 is a single-barrel box culvert with opening dimensions of 3 m (width) by 3.7 m (height) by 58 m (length). The site 2 underpass is a large bridge 8 km west of site 1 (Figure 1). From the perspective of an animal traveling beneath it, the bridge is 94 m wide and (because of a wide median between eastbound and westbound lanes) 150 m long. The river width is approximately 13 m, with approximately 3-m-wide grassy strips on each side to allow the passage of farm vehicles. The remaining area beneath the bridge is sloped with sandy substrate, also passable by wildlife.

Contractors installed approximately 1.6 linear km of 2.4-m-high woven wire fence at each of the study sites on both sides of the interstate, for a total of 3.2 km of fencing per site. The spacing between the horizontal wires gradually decreased further down the fence to prevent smaller animals from passing through. Fencing was constructed at the edge of the tree line, which varied from approximately 2–12 m from the highway shoulder. This design allowed road maintenance staff access to the grassy areas off the roadside to perform routine maintenance activities. Fencing was completed at the site 1 box culvert underpass 11 months prior to the site 2 bridge underpass.

The underpass at each site was centered on the 1.6-km length of fencing, with 0.8 km on both sides of each underpass. At the site 1 box culvert, fencing continued along the interstate above the underpass (as opposed to tying into the culvert wing walls). At the site 2 bridge underpass, fencing ran continuously from the roadside to the area beneath the bridge to prevent wildlife from accessing the median of the interstate. We used the home range size for white-tailed deer to determine the 1.6-km length of fencing at each site (Bissonette and Adair 2008). White-tailed deer home ranges vary widely depending on region, season, and resource availability, but adult males in the region average 2.5 km^2 (Batts 2008, Hewitt 2011).

To allow the escape of deer on the traffic side of the fence to the habitat side, we incorporated 4 jumpouts at each site. These features were situated approximately halfway between the underpass and each fence end. Jumpout design and effectiveness are not discussed herein, however, because the low frequency of wildlife visits to these features from the traffic side of the road allowed only anecdotal presumptions with regard to their effectiveness.

Although fence ends should ideally be designed to end at (or tie into) a landscape feature such as steep topography or another natural barrier to prevent deer from circumventing the fence ends, there were no such natural features at the study sites. We designed the ends of the fencing in 3 different treatments to compare deer activity and DVCs near the fence ends (Figure 2). In treatment 1 (T1), the fence ends angled away from the road, extended 3–6 m, and ended without tying in to a feature. In treatment 2 (T2), the fence ends angled away from the road and tied into the existing 1.2-m right-of-way (ROW) fencing (which ran parallel to and approximately 15 m from the interstate). In treatment 3 (T3), the fence ends remained parallel to the road and tied into a bridge underpass that spanned a low-volume gravel road with a low posted speed limit. It is important to note that the ROW fencing is not high enough to serve as a barrier for deer.

Camera placement

We installed 43 Reconyx Hyperfire (Reconyx, Inc., Holmen, Wisconsin) digital trail cameras in steel enclosures. The cameras use motion sensors to detect the presence of an animal and were programmed to take 3 pictures per triggered event with a 5-second interval between pictures. The cameras use undetectable infrared illumination rather than a flash at night and have a night range up to 15 m and a day range up to 30.5 m.

We installed cameras within 1 week after fencing installation in the same locations as those for the pre-fencing study (Donaldson et al. 2016), evenly spaced in 0.16-km intervals along the fenced sections and attached to the guardrail or poles positioned approximately 1.5 m from the paved shoulder. The cameras' area of detection included the roadside area extending from the highway shoulder to the habitat side behind the fence. At the underpasses, we mounted cameras on trees at the entrances of the box culvert and placed 4 cameras beneath the bridge underpass to capture the entire area beneath the bridge.

Deer carcass data collection and analyses

We obtained deer carcass removal data from handwritten records collected since 2013 by Virginia Department of Transportation's (VDOT) contractor for interstate maintenance. The contractor documented the date and the location of the species to the nearest 0.16 km (0.1 mile) using posted mile marker signs.

At both study sites, we compared 4 years of DVCs before fencing to DVCs post-fencing. Three years of post-fencing DVCs were available for site 1 (2017–2019). Because the fencing at site 2 was completed 1 year after the site 1 fencing, 2 years of post-fencing DVCs were available for site 2 (2018–2019).

To determine whether DVCs increased near the fence ends, we compared pre-fencing DVCs to post-fencing DVCs within 0.4 km and 0.8 km, and 1.6 km of the fence ends. We evaluated DVCs as a whole (combining the DVC data from all of the fence ends) and according to the specific fence end treatments. We used *t*-tests to evaluate differences between pre-fencing and post-fencing DVCs and set $\alpha = 0.05$. To determine whether DVC reductions at the fenced sites were a result of the fencing rather than other variables that influence DVC frequencies, we compared pre- and post-fencing DVCs along the remaining segments of interstate for which deer carcass removal data were available. The segments evaluated began 3 km east of the site 1 fence ends and extended for 43 km, and 3 km west of the site 2 fence ends and extended for 37 km (for a total of 80 km). This allowed for a comparison of DVCs between fenced and non-fenced segments before and after fencing installation at the study sites.

Camera data collection and analyses

The methods we used for camera data documentation and analyses were the same as those for the pre-fencing study, including data analyses of photographs captured at the underpasses, along the roadside, and at the fence end areas (Donaldson et al. 2016). We recorded date, time, species, number of individuals, and direction of travel. In documenting information from photographs captured in pre- and post-fencing studies, we determined wildlife "activity" by documenting the number of animals in a detection event. We defined a detection event as 1 or more animals captured by the camera and separated from the prior detection of the same species by at least 15 minutes to reduce potential double counting.

On some occasions, cameras were not operational for short periods because of battery depletion. We accounted for differences in camera operative days in all analyses. Any results that we reported as the yearly total (e.g., the number of wildlife using the underpasses per year) were calculated by multiplying the average number of wildlife per camera operative day by 365.

For our statistical analyses, we treated the daily counts of deer crossings through the underpasses as having occurred by a group of deer with individuals that varied with regard to the frequency of repeated crossings (i.e., some that frequently crossed, some that occasionally crossed, and some that rarely crossed). With this analysis unit (i.e., a group of deer observed per day), observations were assumed to be independent. We grouped the average daily crossings through each underpass by month and used the Mann-Whitney U test to test the null hypothesis that there were no significant differences in the number of crossings by deer pre- versus post-fencing. We also documented hesitancy behavior as deer approached the underpass; this behavior is indicated by muzzles lowered to the ground (Reed et al. 1975, Gordon and Anderson 2003). We used the 2-proportion Z test to test the null hypothesis that the proportion of deer that exhibited hesitancy behavior upon approaching the underpass before fencing installation was not statistically different than the proportion of deer that exhibited hesitancy behavior upon approaching the underpass after fencing installation. We also tested the null hypothesis that the proportion of deer approaches to the underpass that resulted in crossings rather than retreats was not statistically different before fencing as compared to after fencing. We set $\alpha = 0.05$.

To evaluate differences in roadside deer activity pre- and post-fencing, we compared 2 years of pre-fencing roadside activity data to 2 years of deer activity on the traffic side of the fencing after fencing construction. We evaluated camera data at the fence ends to determine whether there were detectable differences in deer activity among fence end designs (or treatments).

Cost analysis

We compared the costs of the fencing (including site preparation and maintenance costs) with the savings from any DVC reductions at the study sites. We accessed an online database of police-reported crashes to document the most recent 4 years of available DVC data. We evaluated these data to determine the collision severity of police-reported DVCs in the project area. For each DVC at the study site (as determined by a deer carcass removal), we attributed a dollar value based on collision severity. We based this approach on valuations used by traffic engineers in evaluating applications for the VDOT Highway Safety Improvement Program (a federal funding source for safety improvement projects). These valuations use Federal Highway Administration crash cost estimates to attribute dollar values based on the type and severity of the collision (Council et al. 2005).

The annual fencing maintenance cost and the annual crash cost savings at the fenced interstate segments were expressed as a present discounted value. The present discounted value measures the worth of a future amount of money in today's dollars adjusted for interest and inflation. This allowed us to tabulate the annual fencing maintenance and annual crash cost savings with the 1-time fencing installation costs.

Results

DVCs and bear–vehicle collisions

On average, DVCs decreased 92% over the 2 and 3 years post-fencing construction at site 2 and site 1 fenced sections, respectively. There was an average reduction of 8.4 DVCs per 1.6 km per year.

At site 1, in the 4 years pre-fencing, the 1.6-km interstate segment averaged 9.5 DVCs per year. In the 3 years post-fencing, there was an average of 0.3 DVCs per 1.6 km per year (1 DVC occurred the first year post-fencing), representing a DVC reduction of 96.5%.

At site 2, in the 4 years pre-fencing, the 1.6-km interstate segment averaged 8.5 DVCs per year. In the 2 years post-fencing, there was an average of 1 DVC per year (2 DVCs occurred the second year post-fencing), representing a DVC reduction of 88.1%.

No black bears were killed by vehicles at site 1 pre- or post-fencing. At site 2, 1 bear was killed by a vehicle 2 years pre-fencing, and no

Table 1. Annual mean white-tailed deer (*Odocoileus virginianus*)–vehicle collisions pre- and post-fencing within the fenced segments, immediately adjacent to the fence ends, and outside of the study sites beginning 3 km from the fence ends on Interstate 64, Virginia, USA (2013–2019).

		Deer–vehicle collisions (annual mean)				
		Pre-fencing		Post-fencing		
Site	Interstate 64 segments	Annual mean[a]	SD	Annual mean[a]	SD	Difference (%)
Site 1 box culvert	Fenced segment (1.6 km)	9.5	3.9	0.3	0.6	-96.8
	Fence ends (0.6 km)	8.4	1.5	8.8	0.9	+4.0
	Outside of study sites (80 km)	342.0	26.5	298.3	28.1	-12.8
Site 2 bridge underpass	Fenced segment (1.6 km)	8.5	1.9	1	1.4	-88.1
	Fence ends (0.6 km)	6.6	2.1	3.0	1.6	-54.5
	Outside of study sites (80 km)	342.3	22.1	288.5	27.6	-15.7

[a] Pre-fencing data included the 4 years prior to fencing construction (2013–2016 for site 1 and 2014–2017 for site 2). Post-fencing data included 3 years of data for site 1 (2017–2019) and 2 years for site 2 (2018–2019).

Table 2. Mean white-tailed deer (*Odocoileus virginianus*) crossings pre- and post-fencing at the study sites, Interstate 64, Virginia, USA (2013–2019).

Site	Pre- or post-fencing	Mean per day	Mean per year	Increase post-fencing
Site 1 box culvert[a]	Pre-fencing	0.40	145	410%
	Post-fencing	2.04	745	
Site 2 bridge underpass[b]	Pre-fencing	2.60	949	71%
	Post-fencing	4.44	1,620	

[a] Site 1 post-fencing average crossing per day was greater (median = 1.90, n = 26) than pre-fencing crossings (median = 0.23, n = 25).
[b] Site 2 post-fencing average crossing per day was greater (median = 0.95, n = 24) than pre-fencing crossings (median = 0.59, n = 25).

bears were killed post-fencing.

With regard to pre-fencing DVCs versus post-fencing DVCs at the fence ends as a whole (combining DVC data from all fence ends), there were no significant differences within 0.4 km, 0.8 km, 1.6 km, or along the 80-km interstate segments outside of the study sites after fencing (Table 1). We found a 54.5% reduction in DVCs within the 1.6-km fence end segments at site 2, but additional years of DVC data are needed to determine whether the fencing was associated with this reduction (Table 1).

There were no significant differences in pre- and post-fencing DVCs according to fence end treatments (i.e., whether or not they were tied into a feature). We discuss differences in deer activity among the fence end treatments in a subsequent section.

Use of underpasses

Over the 2-year camera monitoring period at each site, cameras were operative an average of 661 days for the post-fencing study (91% of the 2-year monitoring period), compared to an average of 705 days for the pre-fencing study (97% of the 2-year monitoring period). Operative days after fencing installation were slightly lower at site 1 (639 days) than site 2 (683 days).

Deer. Mean deer crossings through the underpasses per day were higher at both sites in the 2 years post-fencing (Table 2). At the site 1 box culvert, the daily average increased from 0.40 crossings per day before fencing to 2.04 per day post-fencing (a 410% increase). Post-fencing at site 2, deer crossings beneath the underpass increased 71%, from an average of 2.60 crossings per day pre- fencing to 4.44 crossings per day post-fencing.

In addition to the increase in the number of crossings, there was a greater proportion of approaches to the site 1 box culvert that resulted in crossings (rather than retreats)

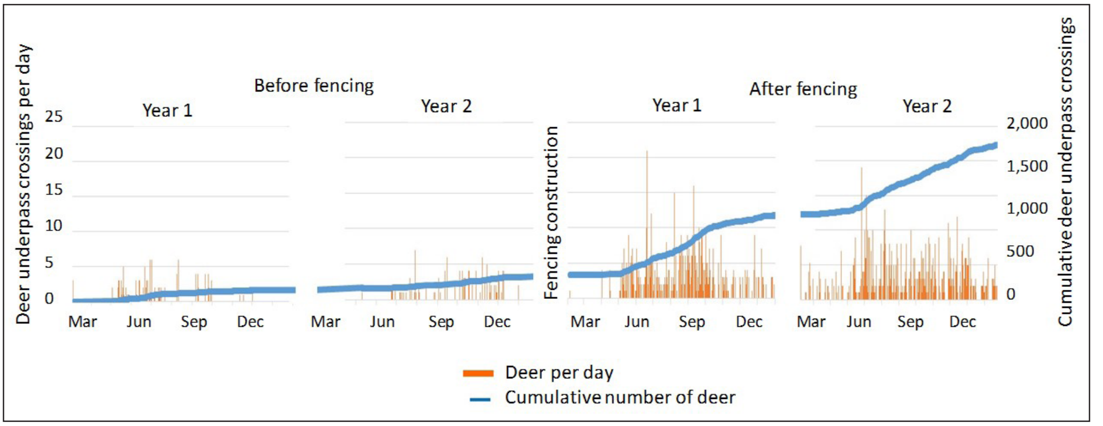

Figure 3. Deer (*Odocoileus* spp.) crossings per day and cumulative number of deer crossings at the site 1 box culvert, Interstate 64, Virginia, USA (2015–2019). Deer per day (represented by the y-axis on the left) and cumulative number of deer (represented by the y-axis on the right) over the 2-year pre-fencing and 2-year post-fencing monitoring studies. Months in each graph are represented on the x-axes, beginning the month camera monitoring was initiated in the pre- and post-fencing studies. The "before fencing" period was March 2014 to February 2016 and the "after fencing" period was February 2017 to February 2019.

post-fencing (80%) than pre-fencing (54%; Z = -11.5, P < 0.001). This is consistent with the decrease in deer hesitancy behavior post-fencing; the proportion of deer that hesitated upon approaching the box culvert post-fencing (30%) was less than that of pre-fencing (43%; Z = -3.8, P < 0.001).

With the larger site 2 bridge underpass, deer that approached the bridge underpass rarely retreated or hesitated pre- or post-fencing. Greater than 92% of approaches resulted in crossings both pre- and post-fencing. We found no significant differences in the proportions of approaches that resulted in retreats or hesitancy behavior pre-fencing compared with post-fencing.

Cumulative deer use of the underpasses increased at a much greater frequency after fencing installation, as evident by the steeper slopes in the post-fencing graphs of site 1 (Figure 3). This increase began approximately 3–4 months after fencing.

Other wildlife. The number of wildlife crossings through each underpass increased post-fencing for most species (i.e., black bear, bobcat, fox spp., opossum, and skunk; Figure 4). Groundhog (*Marmota monax*) crossings at each underpass decreased by one. For species smaller than deer, there was more use of the site 1 box culvert than the site 2 bridge underpass both pre- and post-fencing (Figure 4). Post-fencing at the box culvert, the number of wildlife crossings by species other than deer increased 81% (from 210 crossings per year prior to fencing to 381 per year after fencing). At the site 2 bridge underpass, the average number of wildlife crossings increased 165% (37 crossings per year pre-fencing to 98 per year post-fencing).

Black bears crossed through the site 1 culvert on 8 occasions during the 2-year post-fencing monitoring period (and there were no documented bear crossings during the pre-fencing study [Donaldson et al. 2016] or an earlier 1-year monitoring study [Donaldson 2007]). Numerous crossings by deer, coyote, and bobcats occurred by adults with young.

Deer roadside activity relative to fence end treatments

There was an average reduction of 72% in deer roadside activity pre-fencing and post-fencing on the traffic side of the fence at both study sites. The highest activity on the traffic side of the fence occurred at the fence ends that did not tie into any feature such as ROW fencing. At site 1, which had a 58% reduction in roadside deer activity after fencing, 55% of the post-fencing roadside activity occurred at the eastern fence ends (both of which were T1 treatments that did not tie into any feature). At site 2, where 3 of the 4 fence ends tied into ROW fencing or another bridge underpass, roadside deer activity was reduced 87% after fencing installation (Figure 5).

Deer activity counts at the T1, T2, and T3 fence ends were 124 per year, 11.8 per year, and

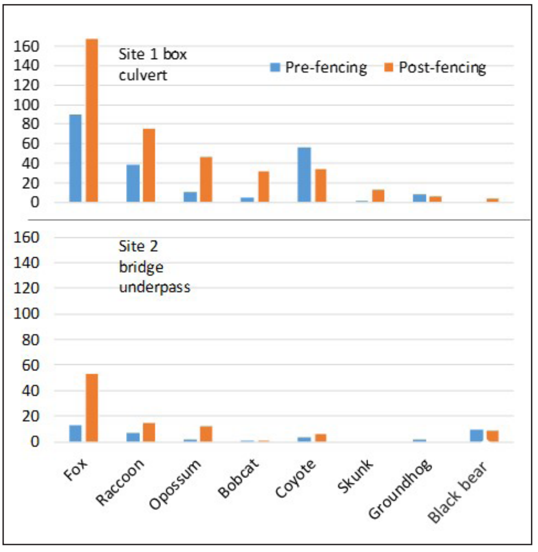

Figure 4. Wildlife crossings per year pre- and post-fencing at the site 1 and site 2 underpasses, Interstate 64, Virginia, USA (2015–2019). Note that different scales are used for each site.

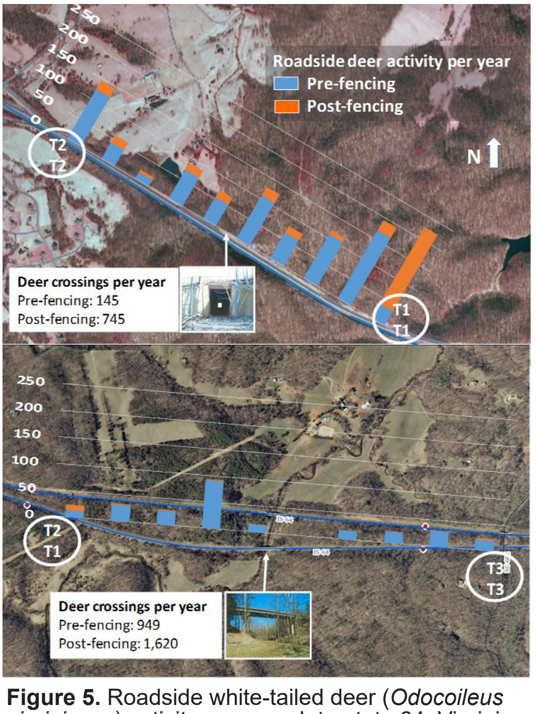

Figure 5. Roadside white-tailed deer (*Odocoileus virginianus*) activity per year, Interstate 64, Virginia, USA, (2015–2019). Roadside deer activity per year at camera locations (blue bars and orange bars), fence end treatments (white circles), and deer crossings per year through the underpasses. Treatment 1 (T1) = fence end does not tie into any structure or landscape feature (N = 3, average deer activity/year = 124); Treatment 2 (T2) = fence end ties in with right-of-way fence (N = 3, average deer activity/year = 11.8); Treatment (T3) = fence end ties in with a bridge underpass that spans a low-volume road (N = 2, average deer activity/year = 3.6).

3.6 per year, respectively. Despite the high deer activity at the site 1 T1 treatments, deer activity at the underpass was much greater, with 745 crossings per year (Figure 5).

Cost analysis

Fencing and associated expenses. A different contractor installed the fencing at each of the 2 study sites. There was a large discrepancy in cost per linear foot ($12 and $29) charged by the contractors, for a cost of $137,088 at 1 site and $335,600 at the other (averaging $265,409). This included site preparation costs (i.e., removal of limbs and low vegetation) that averaged $11,350 per site, traffic control that averaged $16,860 per site, and fencing maintenance that averaged $1,035 per site over 2 years. Fencing maintenance was needed approximately once per year at each site to repair damage from fallen tree limbs and once per site to repair damage from vehicle crashes.

Savings from a reduction of DVCs. We valued a DVC at $8,936. This cost was based on valuations used by traffic engineers in evaluating applications for the Highway Safety Improvement Program, in which property damage only crashes are valued at $8,008 and minor injury crashes are valued at $93,177. Injury costs include medical costs, emergency services, property damage, lost productivity, and monetized quality-adjusted life years (Council et al. 2005). We allocated 99% of the deer carcass removals as property damage only crashes and a conservative 1% to minor injury crashes. We based these percentages on the findings that injuries (with an unknown severity) from police-reported DVCs over the previous 4 years in the study area represented 1% of the number of deer carcass removals during that same time period.

Reflecting a fencing service life of 25 years and an annual discount rate of 0.03 (to adjust for inflation), the total savings from DVC reduction at the study sites were $2,524,870 and $2,171,959 (depending on the fencing contractor), for an average savings per site of $2,348,415.

Economic benefits from crash reductions would exceed fencing costs if DVCs were reduced by <1 DVC per site per year (0.85). In this study, these numbers were greatly exceeded, with an average DVC reduction of

8.5 per site per year. The economic benefits from DVC reductions, predominantly in the form of property damage savings to drivers, begin exceeding fencing costs in an average of 1.8 years.

Discussion

As established in the literature and reflected by the increase in federal programs and state legislation related to wildlife crash reduction efforts, incorporating properly designed and sited wildlife crossings into road construction projects is the most effective means to reduce wildlife crashes while maintaining habitat connectivity (Forman et al. 2003, Schaffer 2019, Fisher 2020). For existing roads where new wildlife crossing construction may not be an affordable option for transportation departments, this study found that enhancing certain existing isolated underpasses with fencing is a valuable opportunity to substantially reduce crashes while maintaining habitat connections for wildlife. While additional study sites would have strengthened the study design, logistical and financial requirements for transportation projects can limit the ability to replicate sites. We therefore concentrated our resources on deploying a large volume of cameras along the roadside and at underpasses to provide a robust dataset on wildlife activity relative to wildlife fencing placement. While there are numerous opportunities to implement this form of mitigation and expand its impact on wildlife crash reduction, it should not be assumed that fencing will increase the use of underpasses by wildlife in all cases. Identifying existing structures that may be suitable for fencing retrofits involves several considerations, including location, structural attributes, and evidence of use by wildlife (Clevenger and Huijser 2011). Additional studies are needed at other locations to better understand the most effective means of using existing infrastructure to increase driver safety and reduce the barrier effect of roads on wildlife.

Although white-tailed deer appear to be ubiquitous in many eastern states, they do not travel randomly throughout the landscape; their movements are influenced by habitat features and resource availability, among other factors (Clevenger et al. 2001, Long et al. 2005, Webb et al. 2009). Highway crossings by deer in Georgia, USA have been found to be performed by a relatively small number of deer; more than 90% of >1,400 highway crossings by deer fitted with Global Positioning System collars were performed by 7 deer within 1 year (Stickles 2014). For wildlife with home ranges that extend across the road, the addition of fencing to strategically selected underpasses can alter their movements to the benefit of driver safety without compromising the ability of wildlife to access needed resources. In this study, deer traveled more frequently and purposefully toward the box culvert once fencing was constructed, as evidenced by the significant reductions in retreats and hesitancy behavior and the increase in crossings. Their awareness of the fencing likely increased their willingness to travel out of their way toward the structure in order to access habitat across the interstate. Once these routes are established, it becomes intergenerational knowledge (Hasapes and Comer 2016, Vartan 2016). Adults traveling through the crossings with their young were frequent occurrences by multiple species in this study; this type of learning behavior likely explains the growth in use of crossing structures over time (Beckmann et al. 2010, Vartan 2016).

Similar to other studies that have found that different species select for different crossing structure designs (Mata et al. 2005, Ford et al. 2017), crossing frequency by species differed between the underpasses evaluated in this study. Although there was greater use of the large bridge underpass by deer and black bears compared to their use of the box culvert, there were more crossings by medium and small mammals through the culvert. The number of crossing at both structures increased for most species post-fencing, indicating that fencing did not benefit some species at the expense of others (Huijser et al. 2016, Jakes et al. 2018).

For white-tailed deer, the structures evaluated in this study fall near the opposite ends of the range of underpasses that they will comfortably use in Virginia (Donaldson 2007). Although deer crossed beneath the large bridge underpass without hesitation, the size attributes of the long enclosed box culvert were close to the lower limit of what deer would consistently use pre-fencing (Donaldson et al. 2016). Fencing increased the use of both underpasses by wildlife, but the addition of fencing to the culvert had the greatest impact on use by deer and black bears. Culvert crossings by bears began to occur only after the fencing was constructed. The large increase in culvert crossings by deer (410%) and the significant decrease in hesitancy behavior and retreats suggest that deer become less reluctant to use structures that are smaller (and/or longer) than what they prefer if they are otherwise restricted from accessing habitat across the highway.

The findings suggest that DVCs did not shift to the fence ends after fencing construction. At both sites, deer activity was much greater at the underpasses than the fence ends. This was the case even at the open fence ends that did not tie into any feature (i.e., deer underpass crossings were >4 times greater than deer activity at the open fence ends). However, the differences in roadside deer activity among the fence end treatments that tied into features (such as ROW fencing) versus those that did not tie into any feature underscores the importance of proper fence end design in minimizing DVC risk. In the pre-fencing study, a significant relationship was found between roadside deer activity and DVCs; DVCs increased as roadside activity increased (Donaldson et al. 2016). Although DVCs did not increase at any of the fence ends in the post-fencing study, there was a high degree of deer activity at the ends that did not tie into a feature. Extending these ends in order to tie them into ROW fencing or another suitable feature would reduce roadside deer activity and the associated risk of DVCs in these areas. In the absence of a tie-in feature, extending fencing beyond wildlife crash hotspots has also been found to decrease the risk of collisions at fence ends (Bissonette and Rosa 2012).

For state DOTs, determining the safety and economic benefits of crash countermeasures is an important means of project selection. States use different methods to develop their crash costs; these approaches are typically based on guidance from the American Association of Highway Transportation Officials, the U.S. Department of Transportation, or the Federal Highway Administration's Highway Safety Improvement Program (Lawrence et al. 2018). In evaluating the potential savings from implementing wildlife crash countermeasures, applying the values used by traffic engineers provides a comparative means of prioritizing projects and making funding decisions. In this study, the calculated savings of $2.3 million per fenced site over the lifetime of the fencing is helping justify the implementation of additional underpass enhancement projects.

Management implications

We found that the addition of wildlife fencing to certain existing isolated underpasses used by wildlife was a highly cost-effective form of DVC mitigation that required a minimal number of crash reductions for the economic benefits to exceed the costs of the fence. This study adds to the growing body of knowledge about the most effective ways we can use existing infrastructure to broaden the scale of wildlife crossing implementation. Strategic decisions on underpass selection and fencing placement can result in the creation of wildlife crossings in areas that may not otherwise be considered because of financial constraints. Implementing this type of mitigation on suitable underpasses in areas with high frequencies of wildlife–vehicle collisions could have a substantial impact on drivers and wildlife, particularly if applied on a larger scale. With fencing placement decisions, fence end design plays a large role in reducing deer access to the traffic side of the fence. DVC risk is reduced by tying fence ends into features or obstacles that will create difficulty for deer attempting to circumvent the ends.

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Literature cited

Batts, G. K. 2008. An assessment of quality deer management on a private hunt club in the Virginia Piedmont. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.

Beckmann, J. P., A. P. Clevenger, M. P. Huijser, and J. A. Hilty, editors. 2010. Safe passages: highways, wildlife, and habitat connectivity. Island Press, Washington, D.C., USA.

Bissonette, J. A., and W. Adair. 2008. Restoring habitat permeability to roaded landscapes with isometrically-scaled wildlife crossings. Biological Conservation 141:484–488.

Bissonette, J. A., and S. Rosa. 2012. An evaluation of a mitigation strategy for deer–vehicle collisions. Wildlife Biology 18:414–423.

Clevenger, A. P., B. Chruszcz, and K. Gunson. 2001. Highway mitigation fencing reduces wildlife–vehicle collisions. Wildlife Society Bulletin 29:646–653.

Clevenger, A. P., and M. P. Huijser. 2011. Wildlife crossing handbook: design and evaluation in North America. FHWA-CFL/TD-11-003. Federal Highway Administration, Washington, D.C., USA.

Council, F., E. Zaloshnja, T. Miller, and B. Persaud. 2005. Crash costs estimates by maximum police-reported injury severity within selected crash geometries. FHWA-HRT-05-051. Federal Highway Administration, McLean, Virginia, USA.

Dodd, N., J. W. Gagnon, S. Boe, and R. E. Schweinsburg. 2007. Role of fencing in promoting wildlife underpass use and highway permeability. Pages 477–478 *in* C. L. Irwin, D. Nelson, and K. P. McDermott, editors. Proceedings of the 2007 International Conference on Ecology and Transportation, Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina, USA.

Donaldson, B. M. 2007. The use of highway underpasses by large mammals and other wildlife in Virginia and factors influencing their effectiveness. Transportation Research Record: Journal of the Transportation Research Board 2011:157–164.

Donaldson, B. M. 2017. Improving animal–vehicle collision data for the strategic application of mitigation. VTRC 18-R16. Virginia Transportation Research Council, Charlottesville, Virginia, USA.

Donaldson, B. M., Y.-J. Kweon, and L. N. Lloyd. 2016. Roadside activity and behavior of white-tailed deer and other wildlife near unfenced underpasses. Transportation Research Record: Journal of the Transportation Research Board 2571:29–38.

Fisher, D. 2020. Legislation to protect wildlife corridors introduced in the Virginia State House. Wildlands Network, Salt Lake City, Utah, USA, <https://wildlandsnetwork.org/blog/legislation-to-protect-wildlife-corridors-introduced-in-the-virginia-state-house/>. Accessed May 3, 2020.

Ford, A. T., M. Barrueto, and A. P. Clevenger. 2017. Road mitigation is a demographic filter for grizzly bears. Wildlife Society Bulletin 41:712–719.

Forman, R. T. T., D. Sperling, J. Bissonette, A. P. Clevenger, C. Cutshall, V. Dale, L. Fahrig, R. France, C. Goldman, K. Heanue, J. Jones, F. Swanson, T. Turrentine, and T. C. Winter. 2003. Road ecology: science and solutions. Island Press, Washington, D.C., USA.

Gagnon, J. W., N. L. Dodd, N. S. C. Sprague, K. Ogren, and R. E. Schweinsburg. 2010. Preacher Canyon wildlife fence and crosswalk enhancement project evaluation. State Route 260. Final Report - Project JPA 04-088. Arizona Game and Fish Department, Phoenix, Arizona, USA.

Gagnon, J. W., C. D. Loberger, S. C. Sprague, K. S. Ogren, S. L. Boe, and R. E. Schweinsburg. 2015. Cost-effective approach to reducing collisions with elk by fencing existing highway structures. Human–Wildlife Interactions 9:248–264.

Gordon, K. M., and S. H. Anderson. 2003. Mule deer use of underpass in western and southeastern Wyoming. Pages 309–318 *in* C. L. Irwin, P. Garrett, and K. P. McDermott, editors. Proceedings of the International Conference on Ecology and Transportation, Center for Transportation and the Environment, North Carolina State University, Raleigh, North Carolina, USA.

Guarino, B. 2020. Climate solutions safe passages. The Washington Post, Washington, D.C., USA, <https://www.washingtonpost.com/graphics/2020/climate-solutions/wyoming-wildlife-corridor/>. Accessed April 12, 2020.

Hasapes, S. K., and C. E. Comer. 2016. Adult white-tailed deer seasonal home range and habitat composition in northwest Louisiana. Journal of the Southeastern Association of Fish and Wildlife Agencies 3:243–252.

Hewitt, D. G, editor. 2011. Biology and management of white-tailed deer. CRC Press, Boca Raton, Florida, USA.

Huijser, M. P., J. W. Duffield, A. P. Clevenger, R. J. Ament, and P. T. McGowen. 2009. Cost-benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada: a decision support tool. Ecology and Society 14(2):15.

Huijser, M. P., E. R. Fairbank, W. Camel-Means, J.

Graham, V. Watson, P. Basting, and D. Becker. 2016. Effectiveness of short sections of wildlife fencing and crossing structures along highways in reducing wildlife–vehicle collisions and providing safe crossing opportunities for large mammals. Biological Conservation 197:61–68.

Huijser, M. P., A. V. Kociolek, T. D. H. Allen, P. McGowen, P. C. Cramer, and M. Venner. 2015. Construction guidelines for wildlife fencing and associated escape and lateral access control measures. Transportation Research Board, Washington, D.C., USA.

Jaeger, J. A. G., and L. Fahrig. 2003. Under what conditions do fences reduce the effects of transportation infrastructure on population persistence? Proceedings of the Infra Eco Network Europe (IENE) Conference, Institute of Nature Conservation, Brussels, Belgium.

Jakes, A. F., P. F. Jones, C. Paige, R. G. Seidler, and M. P. Huijser. 2018. A fence runs through it: a call for greater attention to the influence of fences on wildlife and ecosystems. Biological Conservation 227:310–318.

Jared, D. M., D. A. Osborn, G. J. D'Angelo, K. V. Miller, and R. J. Warren. 2017. Understanding white-tailed deer sensory abilities, behavior, and movement ecology to mitigate deer–vehicle collisions: the value of long-term, collaborative research. Transportation Research Record, 96th Annual Meeting, Washington, D.C., USA.

Kintsch, J., P. Cramer, P. Singer, M. Cowardin, and J. Phelan. 2020. State Highway 9 wildlife crossings monitoring—year 4 progress report. Study Number 115.01, Colorado Department of Transportation, Denver, Colorado, USA.

Klar, N., M. Herrmann, and S. Kramer-Schadt. 2009. Effects and mitigation of road impacts on individual movement behavior of wildcats. Journal of Wildlife Management 73:631–638.

Lawrence, M., A. Hachey, G. Bahar, and F. Gross. 2018. Highway safety benefit-cost analysis guide. Report No. FHWA-SA-18-001. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., USA.

Long E. S., D. R. Diefenbach, C. S. Rosenberry, B. D. Wallingford, and M. D. Grund. 2005. Forest cover influences dispersal distance of white-tailed deer. Journal of Mammalogy 86:623–629.

Mata, C., I. Hervas, J. Herranz, F. Suarez, and J. E. Malo. 2005. Complementary use by vertebrates of crossing structures along a fenced Spanish motorway. Biological Conservation 124:397–405.

McCollister, M. F., and F. T. Van Manen. 2010. Effectiveness of wildlife underpass and fencing to reduce wildlife–vehicle collisions. Journal of Wildlife Management 74:1722–1731.

Parker, I. D., R. R. Lopez, N. J. Silvy, D. S. Davis, and C. B. Owen. 2011. Long-term effectiveness of US 1 crossing project in reducing Florida Key deer mortality. Wildlife Society Bulletin 35:296–302.

Reed, D. F., T. N. Woodward, and T. M. Pojar. 1975. Behavioral response of mule deer to a highway underpass. Journal of Wildlife Management 39:361–167.

Robinson S. J., M. D. Samuel, D. L. Lopez, and P. Shelton. 2012. The walk is never random: subtle landscape effects shape gene flow in a continuous white-tailed deer population in the Midwestern United States. Molecular Ecology 21:4190–4205.

Rytwinski, T., and L. Fahrig. 2012. Do species life history traits explain population responses toroads? A meta-analysis. Biological Conservation 147:87–98.

Sawyer, H., C. Lebeau, and T. Hart. 2012. Mitigating roadway impacts to migratory mule deer—a case study with underpasses and continuous fencing. Wildlife Society Bulletin 36:492–498.

Schaffer, K. 2019. New Mexico Governor signs first-of-its-kind Wildlife Corridor Act into law. Wildlands Network, Salt Lake City, Utah, USA, <https://wildlandsnetwork.org/blog/new-mexico-governor-signs-first-of-its-kind-wildlife-corridor-act-into-law>. Accessed February 3, 2021.

Senate Environment and Public Works Committee. 2019. America's Transportation Infrastructure Act of 2019. Senate Environment and Public Works Committee, Washington, D.C., USA, <https://www.capito.senate.gov/imo/media/doc/ATIA%20-%20Summary.pdf>. Accessed May 3, 2020.

State Farm. 2020. How likely are you to have an animal collision? State Farm, Bloomington, Illinois, USA, <https://www.statefarm.com/simple-insights/auto-and-vehicles/how-likely-are-you-to-have-an-animal-collision>. Accessed March 20, 2020.

Stickles, J. H. 2014. Using GPS telemetry to assess deer–vehicle collision risk in Georgia. Thesis, University of Georgia, Athens, Georgia, USA.

Vartan, S. 2016. How wildlife bridges over highways help make animals—and people—safer. National Geographic, Washington, D.C., USA, <https://www.nationalgeographic.com/animals/2019/04/

wildlife-overpasses-underpasses-make-animals-people-safer/#close>. Accessed February 12, 2020.

Ward, A. L. 1982. Mule deer behavior in relation to fencing and underpasses on Interstate 80 in Wyoming. Transportation Research Record: Journal of the Transportation Research Board 859:29–38.

Webb, S. L., S. K. Riffell, K. L. Gee, and S. Demarais. 2009. Using fractal analyses to characterize movement paths of white-tailed deer and response to spatial scale. Journal of Mammalogy 90:1210–1217.

Woods, J. G. 1990. Effectiveness of fences and underpasses on the Trans-Canada Highway and their impact on ungulate populations project. Report to Banff National Park, Environment Canada Parks Service, Banff, Alberta, Canada.

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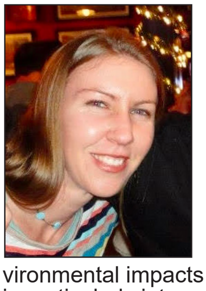

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