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research report

A Toolkit of Measures for Reducing Animal-Vehicle Collisions

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16. Abstract

Animal-vehicle collisions are a growing concern in terms of human safety; costs related to injury, property damage, and disposal; and the viability of wildlife populations. These collisions are rapidly increasing throughout the United States, and Virginia is consistently ranked among the states with the highest number of deer-vehicle collisions, in particular. Federal and state agencies have consequently placed added pressure on transportation departments to implement measures to reduce these incidents.

It is often unclear to transportation practitioners, however, which mitigation measures are effective and where, how, and under what circumstances to use a measure for a particular road project. Although determining a definitive solution for any particular situation is difficult, the toolkit developed in this study is intended as a "quick" guide to provide information on the latest research available on the effectiveness of various mitigation measures to reduce animal-vehicle collisions. More extensive information on one particularly effective technique, wildlife crossings, is provided to assist in implementation and design decisions.

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FINAL REPORT

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ABSTRACT

Animal-vehicle collisions are a growing concern in terms of human safety; costs related to injury, property damage, and disposal; and the viability of wildlife populations. These collisions are rapidly increasing throughout the United States, and Virginia is consistently ranked among the states with the highest number of deer-vehicle collisions, in particular. Federal and state agencies have consequently placed added pressure on transportation departments to implement measures to reduce these incidents.

It is often unclear to transportation practitioners, however, which mitigation measures are effective and where, how, and under what circumstances to use a measure for a particular road project. Although determining a definitive solution for any particular situation is difficult, the toolkit developed in this study is intended as a "quick" guide to provide information on the latest research available on the effectiveness of various mitigation measures to reduce animal-vehicle collisions. More extensive information on one particularly effective technique, wildlife crossings, is provided to assist in implementation and design decisions.

FINAL REPORT

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INTRODUCTION

The rise in animal-vehicle collisions in the United States, largely a result of increased habitat fragmentation from housing and infrastructure development, is drawing national attention. Although some species suffer considerable population losses from these collisions (Iuell et al., 2003; Forman et al., 2003), large species such as deer pose a high risk for drivers. More than 1.5 million traffic accidents involving deer-vehicle collisions (DVCs) occur in the United States each year, resulting in approximately 200 human deaths, more than 4,000 human injuries, and $1.1 billion in property damage (cited in Hedlund et al., 2003). In Virginia, an estimated 43,000 DVCs occurred in 2005. This is a 13% increase from the previous year, and Virginia has the sixth highest number of DVCs of all U.S. states. At the 2006 average reported property damage cost of $2,800 per DVC (M. Miles, personal communication, 2006), these collisions can cost Virginia taxpayers $120.4 million in property damage in 1 year alone.

Animal-vehicle collisions generally result from animals attempting to access habitat on the other side of a road. For many species, roads act as barriers to this movement, restricting populations from necessary behaviors associated with feeding, reproduction, natal dispersal, and responses to seasonal and environmental changes. This can lead to serious declines in species' populations (Forman et al., 2003; Foresman, 2004). Isolated populations face an increased probability of inbreeding as genetic exchange between them decreases, thereby increasing the risk of eventual extirpation. Local extirpation can also result for seemingly healthy populations because of catastrophic weather events, sudden disease outbreaks, excessive predation, nest failure, and other causes.

Animal-vehicle collisions are eliciting a response from federal and state agencies from the driver safety aspect, and this barrier effect of roadways is also generating concern for wildlife viability. The 2005 Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) contains directives for designing projects and processes to reduce these impacts to wildlife and driver safety. As part of the legislation, the U.S. Department of Transportation (DOT) is charged with conducting a comprehensive study on the causes and impacts of wildlife-vehicle collisions. One of the highway improvement measures listed in the Highway Safety Section of the legislation (Subtitle D, Section 1401) is "the addition or retrofitting of structures or other measures to eliminate or reduce accidents involving vehicles and wildlife." An unprecedented provision also requires that transportation planners consider wildlife conservation during the planning process.

In addition to the Virginia Department of Transportation's (VDOT) concerns and responsibilities for driver safety and environmental stewardship, the financial aspect of carcass removal and disposal is a significant matter. Although VDOT does not maintain a statewide database that tracks costs associated with these activities, the disposal cost for the Reston Area Headquarters in Fairfax County alone is $65 per trip (T. Barnes, personal communication, 2004). Based on the estimated 43,000 DVCs from 2005 (M. Miles, personal communication, 2006), these disposals potentially cost VDOT millions of dollars annually.

For transportation agencies, reducing animal-vehicle collisions may seem an overwhelming undertaking with no tangible solution. It can be unclear whether any mitigation measures are effective and where, how, and under what circumstances to use a measure for a particular road project. As transportation agencies are increasingly faced with regulatory and public pressure to manage these collisions, methods to reduce animal-vehicle collisions and allow for safe wildlife movement are being developed and tested. More than ever before, information and opportunities for implementing effective mitigation are available.

PURPOSE AND SCOPE

The objective of this study was to develop a toolkit that provides information on measures to consider to reduce animal-vehicle collisions and/or to provide safe wildlife movement across a roadway. This information will be particularly useful to VDOT transportation planners and environmental staff during the transportation planning and environmental scoping processes when a proposed project may result in an increased risk of animal-vehicle collisions. The toolkit is not intended to be a comprehensive analysis of mitigation techniques, but rather an attempt to consolidate recent research findings and provide facts to assist in making informed decisions. This document is intended as a "quick" guide; the information therefore does not address most species-specific issues.

The information occasionally references a geographic information system (GIS) analysis conducted by the Virginia Department of Conservation and Recreation's (DCR) Division of Natural Heritage (DCR-DNH) entitled the Virginia Natural Landscape Assessment (VANLA). VANLA is a mapping project that identifies large patches of natural landcover (habitat cores) and the habitat linkages connecting these areas (habitat corridors). These data will be considered for inclusion in VDOT's GIS Integrator and/or Comprehensive Environmental Data and Reporting system (CEDAR) in 2007. Through these data management systems, VANLA can be accessed by transportation planners and environmental staff to screen a proposed project location for its vicinity to important habitat areas and wildlife habitat corridors. Donaldson and Weber (2006) describe the VANLA methodology and its application for VDOT staff. Because areas with high frequencies of animal-vehicle collisions are often located where roadways intersect with habitat corridors (Finder et al., 1999; Romin, 1994), using VANLA in conjunction with this toolkit would be an effective means of planning for mitigation.

METHODS

A literature search was conducted to acquire the most recent information on effective measures to reduce animal-vehicle collisions and/or provide habitat connectivity across transportation corridors. Conference sessions were attended, and publications from the International Conference on Ecology and Transportation and meetings of the Transportation Research Board were searched. Online databases, including the National Transportation Library, Web of Science, and Transportation Research Board Research in Progress were also searched. Some of the information was taken from previously consolidated summaries regarding the effectiveness of various mitigation measures. Research conducted subsequent to these reviews supplemented this information to provide the most recent findings in this area.

RESULTS

Effectiveness of Mitigation Techniques to Reduce Animal-Vehicle Collisions

SAFETEA-LU contains an unprecedented number of references to wildlife conservation and animal-vehicle collision reduction. Likely a result of the greater attention paid to these issues at the federal level, VDOT is increasingly faced with requests and directives from state natural resource and regulatory agencies to consider measures to reduce the impacts of highway projects on wildlife and the incidents of animal-vehicle accidents. As other states are facing similar pressure, transportation agencies across the nation are funding more research on effective mitigation methods to manage these issues.

DVCs are particularly troublesome because they cause more human injury, death, and property damage than any other type of animal-vehicle collision. Table 1 summarizes the current state of the knowledge of 17 potential DVC reduction techniques. The complexity and variability of the DVC problem often create difficulties in designing studies that will provide conclusive results. Many measures show potential but require additional research before conclusions regarding their effectiveness can be reached.

Measures Determined to Be Ineffective or to Have Limited Effectiveness

Three mitigation techniques, deer whistles (cited in Hedlund et al., 2003), deer reflectors (D'Angelo, 2006), and deer flagging models (placards resembling a deer with the tail raised in a warning position as a signal to deer not to enter the roadside; cited in Hedlund et al., 2003), have been studied sufficiently to be categorized as ineffective. Several techniques appear to be either ineffective or somewhat effective in specific situations but are impractical to implement (cited in Hedlund et al., 2003; cited in Knapp et al., 2004). Deer repellants and intercept feeding, for example, may be effective for a limited duration in localized areas but would be difficult to implement consistently and are ineffective as long-term strategies. Meyer (2006) found that passive deer crossing signs, i.e., permanent signs showing an illustration of a deer, are not an effective tool for mitigating DVCs, but further studies are needed before this can be determined conclusively.

Measures Known to Be Effective or to Require Additional Research

Figure 1 separates mitigation measures into those that affect driver speed or attentiveness, those that prevent animals from entering the road, and those that facilitate movement between habitats. These measures include those listed in Table 1 that either are effective (i.e., wildlife crossings with fencing) or may be effective but require additional research.
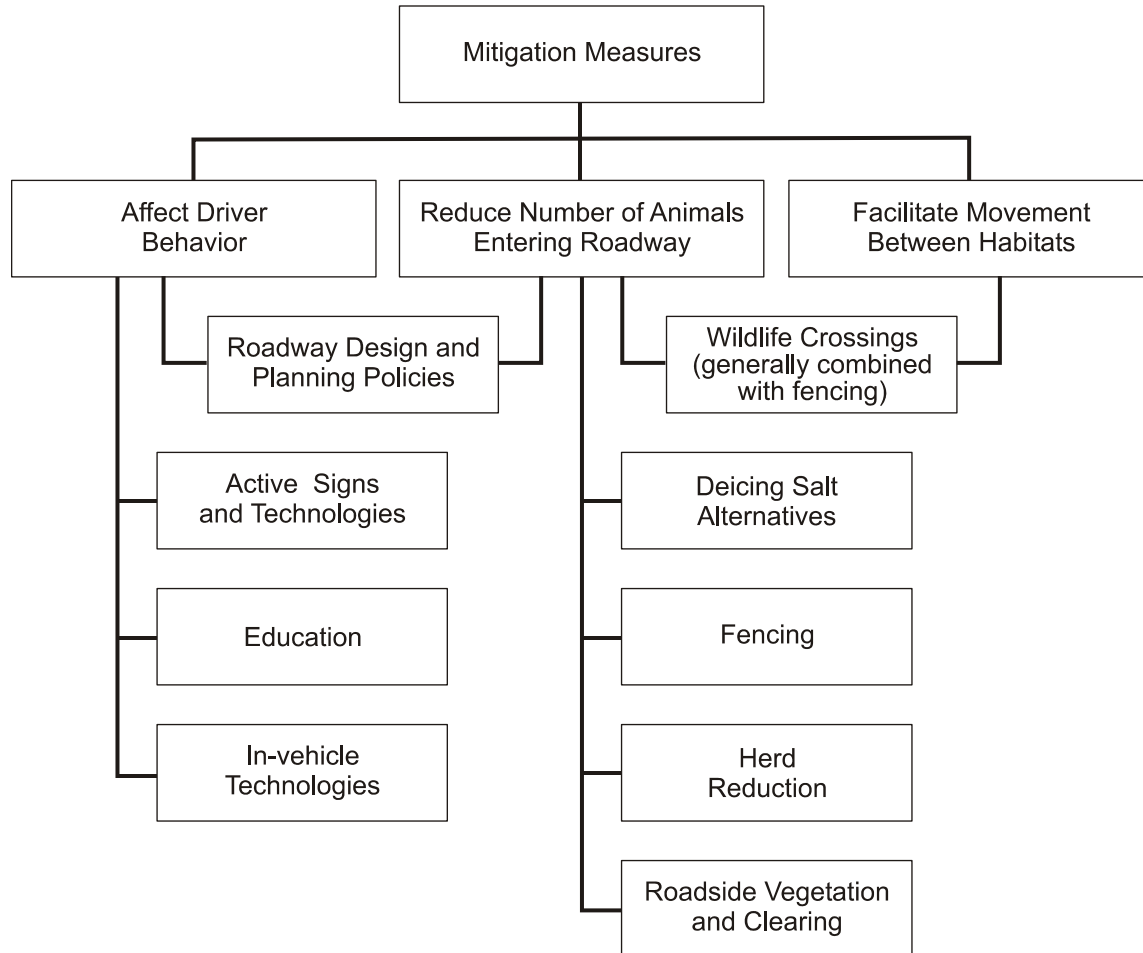
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                          │ Mitigation Measures │
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           ┌──────────────────────┼──────────────────────┐
  ┌────────────────┐   ┌──────────────────────┐   ┌──────────────────┐
  │ Affect Driver  │   │ Reduce Number of     │   │ Facilitate       │
  │ Behavior       │   │ Animals Entering     │   │ Movement Between │
  │                │   │ Roadway              │   │ Habitats         │
  └────────────────┘   └──────────────────────┘   └──────────────────┘
        ┌─────────────────────┐   ┌──────────────────────────┐
        │ Roadway Design and  │   │ Wildlife Crossings       │
        │ Planning Policies   │   │ (generally combined      │
        │                     │   │ with fencing)            │
        └─────────────────────┘   └──────────────────────────┘
        ┌─────────────────────┐   ┌──────────────────────────┐
        │ Active Signs        │   │ Deicing Salt             │
        │ and Technologies    │   │ Alternatives             │
        └─────────────────────┘   └──────────────────────────┘
        ┌─────────────────────┐   ┌──────────────────────────┐
        │ Education           │   │ Fencing                  │
        └─────────────────────┘   └──────────────────────────┘
        ┌─────────────────────┐   ┌──────────────────────────┐
        │ In-vehicle          │   │ Herd                     │
        │ Technologies        │   │ Reduction                │
        └─────────────────────┘   └──────────────────────────┘
                                  ┌──────────────────────────┐
                                  │ Roadside Vegetation      │
                                  │ and Clearing             │
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Figure 1. Effective or Potentially Effective Mitigation Measures to Increase Driver Safety and Reduce Adverse Effects of Roads on Wildlife

Active Signs and Technologies

Technology-based deployments, such as animal-detection driver-warning systems, show potential in reducing DVC incidents but require further research before they are applicable for general use (Figure 2A). These systems are designed to detect wildlife on the roadside and respond with flashing warning lights for drivers. Western Transportation Institute (WTI) at Montana State University recently completed the first phase of a multi-year study to understand the impact of advanced technologies on DVC reduction (Huijser et al., 2006). The authors report that although the system they tested does detect large animals reliably, factors such as the location on the road, the weather, and blind spots in the system keep it from being a completely

Table 1. Effectiveness of DVC Reduction Techniques

DVC Reduction Technique	Determined Effective	Limited Effectiveness or Appears Ineffective	Determined Ineffective	Requires Additional Research	Comments	Source
In-vehicle technologies (infrared vision or sensors)				✓	Potential to reduce DVCs	Cited in Hedlund et al. (2003) and cited in Knapp (2004)
Deer whistles			✓			Cited in Hedlund (2003)
Roadway lighting		✓			May have limited effectiveness in specialized situations	Cited in Helund et al. (2003) and cited in Knapp (2004)
Speed limit reduction		✓			Appears ineffective	Cited in Helund et al. (2003) and cited in Knapp (2004)
Deicing salt alternatives				✓	Use of roadway salt has potential to increase animal mortality in some manner	Cited in Knapp (2004)
Deer-flagging models			✓			Cited in Hedlund et al. (2003)
Intercept feeding (feeding stations outside roadway)		✓			May have limited effectiveness in specialized situations	Cited in Hedlund et al. (2003)
Passive deer crossing signs		✓				Cited in Helund et al. (2003) and cited in Knapp (2004)
Technology-based deployments (active signs and technologies)				✓	Appears promising in specific situations	Cited in Helund et al. (2003) and cited in Knapp (2004)
Roadside reflectors or Mirrors			✓			D'Angelo (2006)
Deer repellants		✓				Cited in Helund et al. (2003) and cited in Knapp (2004)
Herd reduction				✓		
Public information and education				✓	Regular education is important, although effects are difficult to assess	Cited in Knapp (2004)
Roadside vegetation management (plant choices and clearing)				✓		Cited in Helund et al. (2003) and cited in Knapp (2004)
Exclusionary fencing	✓				Effective when combined with wildlife crossings.	Cited in Helund et al. (2003) and cited in Knapp (2004)
Wildlife crossings	✓				Effective, particularly when combined with fencing	Cited in Helund et al. (2003) and cited in Knapp (2004)
Roadway design and planning policies				✓	Appears that planning decisions may help mitigate DVC problem	Cited in Knapp (2004)

Figure 2. An animal-detection driver warning system (A) and a dynamic message sign displaying a wildlife advisory (B). Photo credit: Marcel Huijser (A) and Amanda Hardy (B), Western Transportation Institute, Montana State University. Used with permission.

reliable method for detecting all wildlife along the road. The system will be further evaluated over the next 2 years. WTI estimated the yearly costs, including all maintenance and operations activities, at $31,300 per year (Huijser et al., 2006). Four state departments of transportation (New Mexico, Arizona, California, and Nevada) have plans to use such systems along highways with heavy animal mortalities.

WTI also studied the effectiveness of dynamic message signs (displaying varying wildlife advisory messages) as a speed reduction tool (Figure 2B; Hardy et al., 2006). Although a speed and driver survey suggested that dynamic signs can reduce motorist speed and provide drivers with a heightened awareness, further research is needed before conclusions can be reached regarding their effectiveness in reducing animal-vehicle collisions.

Education

Seasonal campaigns educating motorists about animal-vehicle collisions are common in many localities. DVCs are most frequently targeted in education campaigns, particularly in the fall or spring when these collisions are more frequent. State and private organizations, including transportation agencies, regularly issue press releases, commercials, brochures, and web pages warning drivers to pay close attention to deer on the roadway and suggesting measures to avoid a collision or reduce the potential for injury if one is unavoidable.

The Metropolitan Washington Council of Governments, comprising 20 local governments in the District of Columbia, Maryland, and Virginia, recently released a wildlife-vehicle collision avoidance report and public safety video to its member jurisdictions (Metropolitan Washington Council of Governments, 2006). The report serves as a policy

statement that calls for the development of a seasonal awareness program and a driver's education package for each jurisdiction to consider. The Virginia Department of Game and Inland Fisheries provides press releases each fall and maintains DVC avoidance information on its website (Virginia Department of Game and Inland Fisheries, 2006). Although generally viewed as an important strategy (Knapp, 2004), the effectiveness of public education campaigns in reducing DVC has not been studied.

In-Vehicle Technologies

This form of mitigation equips vehicles with infrared technologies that can sense an animal and alert the driver to its presence. Some in-vehicle systems are also designed to enhance driver night vision. The efficacy of these systems on reducing animal-vehicle collisions has not been studied.

Roadway Design and Planning

Roadway design includes the consideration of elements such as speed limit, roadway curvature, and road cross section. Gunther et al. (1998) suggested that narrow lanes and a curvilinear design may reduce vehicle speed and subsequent animal mortality. Traffic calming measures, including temporary or seasonal closure of roads to avoid periods of high numbers of animal crossings, have also been mentioned as possible options to reduce animal-vehicle collisions, but research is needed to document their effectiveness. A traffic calming measure is annually conducted along a section of Riverside Drive in Richmond, Virginia. The manager of James River Park spearheaded an effort to close a 0.5-mi section of this road during rainy nights from February through March during the mass movement and breeding of spotted salamanders. This effort is associated with a reduction in deaths in the salamander population from up to 30 per night to approximately 1 per season. Publicity for this project and signs informing drivers of why and when the road is closed have helped foster community support, and the park staff has received no complaints regarding this temporary road closure (R. White, personal communication, 2006).

Roadway planning includes evaluations that can lead to measures to reduce the adverse effects of a road project on wildlife, habitat, and animal-vehicle collisions. This can range from site-specific project planning to statewide habitat assessments in relation to the transportation network. Analyses compiled from habitat data, animal movement information, and/or high-frequency roadkill locations are used to inform transportation planners prior to the design phase of a project (Schaefer and Smith, 2000; Austin et al., 2005; Singleton and Lehmkuhl, 2006). This information allows transportation staff to implement mitigation or avoidance measures in accident-prone sites. Although project planning encompasses a variety of planning processes and measures, creating difficulty in documenting the effectiveness of "roadway planning" as a whole, implementing appropriate roadway planning measures is likely to increase safety for drivers and wildlife. For example, using animal movement information in road placement decisions can lead to the implementation of effective avoidance or mitigation measures to reduce the likelihood of a collision.

Deicing Salt Alternative

Because deer are attracted to salts, road salt application can encourage their presence in the roadway, and it thought that this may increase the likelihood of a collision (Bruinderink and Hazebroek, 1996; cited in Knapp, 2004). An increase in DVCs as a result of salt application has not been verified by research, and studies are needed before determining whether deicing salt alternatives are an effective and feasible option.

Roadside Vegetation and Clearing

Wildlife can be attracted to the roadway based on vegetation found in the right of way. It has generally been suggested that the presence of certain vegetation along the road may increase the likelihood of a collision (cited in Knap, 2004). Studies have not sufficiently concluded, however, whether and which plant species impact DVCs.

In addition to reducing forage that may attract deer, clearing vegetation along the roadside is thought to provide drivers a clearer view of animals along the road. Drivers are less likely to hit a deer if they see a deer in advance (Bashore et al., 1985). Because roadside clearing raises other issues such as aesthetics and the costs associated with acquiring roadside right of way and keeping it cleared from vegetation, the practicability of this measure requires further analysis.

Herd Reduction

The Virginia Department of Game and Inland Fisheries and the U.S. Department of Agriculture have applied herd reduction programs in some areas in Virginia. From 1993 to 2003, Lynchburg hunters and wildlife specialists reduced the city's deer population by more than 2,600. DVCs decreased approximately 50% over this 10-year period (Lynchburg Police Department, unpublished data, 2006). Similar DVC reductions occurred in the City of Blacksburg following a deer control program in 2000 (Blacksburg Police Department, unpublished data, 2006). Many issues impede implementation of this technique, however, including its practicability and effectiveness over large areas, public controversy, the cost of effective herd reduction programs, and safety concerns with herd reduction near urban areas and neighborhoods.

Fencing

Although fencing has been shown to be highly effective in keeping animals from entering the roadway (Bashore et al., 1985; Ward, 1982), it increases the adverse effects of habitat fragmentation and can reduce the viability of wildlife populations that depend on movement for foraging, breeding, or natal dispersal (Forman et al., 2003; Foresman, 2004). When combined with properly designed wildlife crossings, however, these measures have repeatedly been shown to be the most effective measures for reducing animal-vehicle collisions and allowing for habitat connectivity across a roadway (Clevenger et al., 2001; Donaldson, 2005).

Wildlife Crossings

Wildlife crossings (Figure 3) and exclusionary fencing, particularly when used together, are the only methods with sufficient scientific evidence to be regarded as highly effective countermeasures (cited in Hedlund et al., 2003; cited in Knapp et al., 2004). These techniques have consistently yielded animal-vehicle collision reductions, and as a result, their use is increasing throughout the United States. Wildlife crossings with fencing have resulted in a 96% reduction in roadkills for ungulate (including deer) species on the Trans-Canada Highway (Parks Canada, 2004). Given the increasing attention on wildlife crossings in the United States, research is underway regarding specific features that influence their use. Through a pooled-fund study by the National Cooperative Highway Research Program, a 3-year comprehensive evaluation of the use and effectiveness of wildlife crossings is underway (Bissonette et al., unpublished data). The Virginia Transportation Research Council (VTRC) recently completed a study evaluating various underpasses to determine the size and location features of effective wildlife crossings for whitetail deer and other wildlife in Virginia (Donaldson, 2005).

Figure 3. (A) A box culvert, 15 x 20 ft, in Fairfax County, Virginia. (B) A 984-ft bridge over a wetland in Chesapeake, Virginia, modified with a "boardwalk" to provide a dry passageway for wildlife.

Wildlife Crossing Considerations and Design

When to Consider a Wildlife Crossing

Wildlife crossings should be considered under one or more of the following circumstances:

- A road leads to great damage or loss of important habitat (Iuell et al., 2003).

- The connectivity between habitats in the landscape is impaired by the road project (Iuell et al., 2003). This includes where a planned road project interferes with an important habitat corridor (Figure 4).
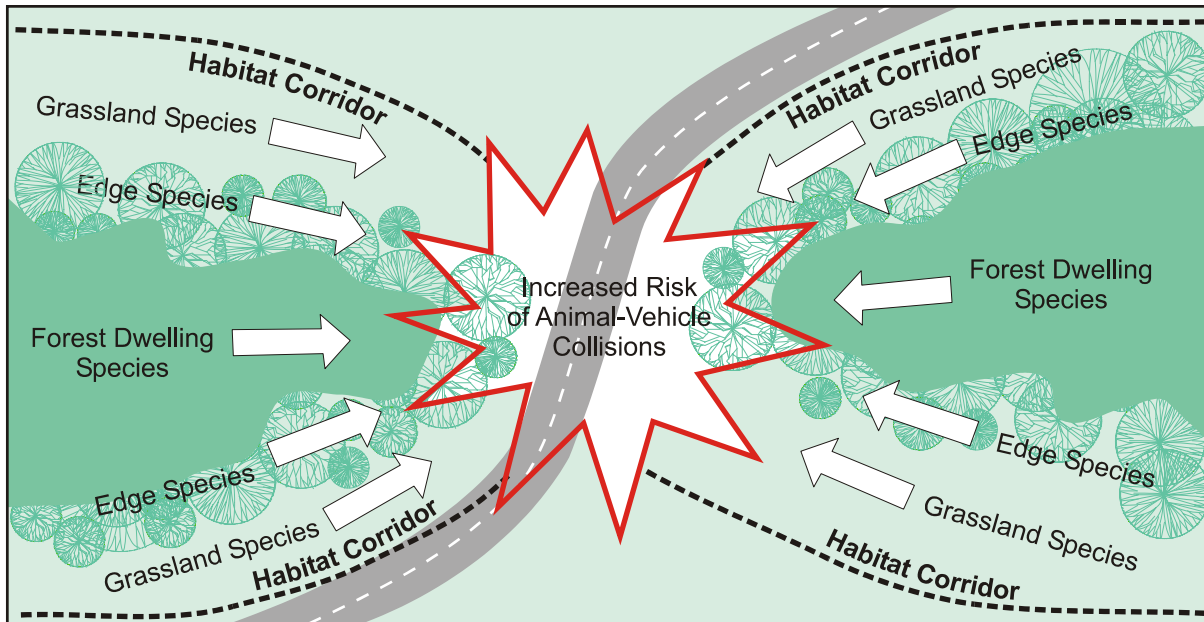
Figure 4. Convergency Point of Different Habitat Types, Illustrating Higher-Risk Area for Animal-Vehicle Collisions

- Wildlife crossings are considered to be a suitable solution for mitigating the barrier effect (whereby road conditions or traffic creates a barrier to wildlife movement) in the specific context (Iuell et al., 2003).

- A road project affects species particularly sensitive to barriers and road mortality (Iuell et al., 2003).

- The road is fenced along its length (Iuell et al., 2003).

- The area has a high frequency of animal-vehicle collisions.

- An existing structure (bridge or culvert) in an area of important wildlife habitat or high animal mortality can be modified to accommodate wildlife passage,

- Any of the previous conditions is met *and* the habitat on either side of a road project is not planned for significant alteration or development in the foreseeable future.

Habitat Corridors

Habitat corridors often illustrate habitat convergency points (Forman, 1995) whereby different habitat types converge and create a funnel effect across the landscape. Corridors act as a conduit for wildlife, which move either inside or alongside the corridor (Forman, 1995). Some species, such as deer, prefer the edge habitat (habitat along the interface of woodlands and fields) within a corridor. Because corridors represent a high frequency of animal movement, there is an increased risk of animal-vehicle collisions where a corridor intersects a roadway (Figure 4).

Research supports this concept that animal-vehicle collisions are spatially aggregated and based on landscape elements that animals are likely to follow in their regular movements (Cain et al., 2003; Hubbard et al., 2000; Bashore et al., 1985). Deer and many other species commonly follow riparian corridors, in particular, in their daily and seasonal movements. High-frequency DVC areas are often located where roadways intersect with riparian travel corridors (Finder et al., 1999; Romin, 1994). The most effective location for mitigation is therefore the area at which these corridors cross a roadway.

Wildlife crossings can be especially effective in areas where a road project intersects with habitat cores and corridors identified by DCR-DNH's VANLA (Donaldson and Weber, 2006). This habitat data will be considered for inclusion in VDOT's environmental data management system, CEDAR. If incorporated into CEDAR, VDOT staff can access these mapped locations of significant habitat areas (cores) and the habitat corridors connecting those habitats. Where a road bisects a habitat corridor, for example, placement of one or more crossing structures would allow wildlife movement to continue unimpeded across the right of way. Wildlife crossings should not necessarily be considered based solely on the immediate context of an isolated road project but rather on the habitat distribution, development, and other circumstances surrounding the project area on a broader scale.

Modifying Existing Structures to Accommodate Wildlife Passage

Wildlife crossings can be structures designed specifically for wildlife passage or can be those designed for other purposes and modified to encourage use by animals. Structures originally designed to span or transport water beneath a road, for example, can be modified to accommodate animal movement. Improving existing bridges and culverts to facilitate wildlife passage can result in substantial gains to wildlife and drivers for little investment (Forman et al., 2003). The modification of structures may be a particularly feasible and cost-efficient option for states that are investing in road maintenance projects more than new road construction.

Modifications to existing drainage pipes or culverts include (1) enlarging the structure; (2) adding a dry shelf/ledge above the water level (if the culvert is permanently or seasonally filled with water; Figure 5); (3) adding natural substrate to the bottom of the culvert, such as dirt and rocks; (4) planting vegetation leading to the entrance of the culvert to serve as cover; and (5) adding fencing on either side of the culvert.

Modifications to existing bridges that span a creek or river and that do not provide sufficient space for animal movement alongside the waterway include (1) adding bridge extension(s) to provide more room for movement, (2) adding an area of dry substrate (in cases where a bridge spans a wetland), (3) planting vegetation leading to the entrance of the bridge to serve as cover, and (4) adding fencing on both sides of the bridge. It is recommended that approximately 30 ft of bank vegetation be provided on both sides of a river beneath a bridge to promote animal movement (O'Brien, 2006), but narrower strips have also been found to be effective (Donaldson, 2005).

This approach is proving successful at the Route 17 Bridge east of the Great Dismal Swamp National Wildlife Refuge in Chesapeake, Virginia (Figure 4B). The U.S. Army Corps of
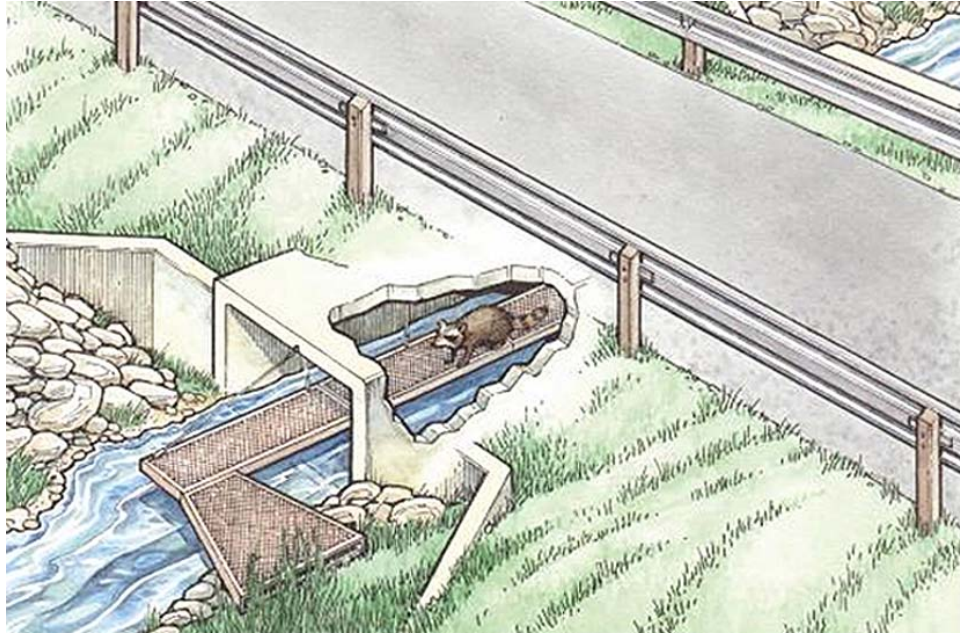
Figure 5. Drainage Culvert Modified with Shelf for Wildlife Passage (a Critter-Crossing™ Animal Access Shelf). Photo credit: Roscoe Steel & Culvert Co. Used with permission.

Engineers determined that in order to avoid disturbance to a high-quality wetland habitat, construction of Route 17 should include a 984-ft-long bridge that spans the wetland. Although the main function of the bridge was to avoid impacts to the wetland, VDOT constructed "boardwalks" at the far ends of the bridge to serve the dual purpose of facilitating wildlife movement. These boardwalks consist of slightly elevated mounds of dirt and mulch, each approximately 20 ft wide. To encourage further wildlife use of the bridge and prevent animal-vehicle collisions, 10,000 ft of 10-ft-high fencing was erected on both sides of the bridge. VTRC camera monitoring beneath the bridge documented hundreds of wildlife using the structure in its first year. Nearly all wildlife avoid the wet areas and cross along the boardwalk. The addition of the boardwalks to encourage wildlife use were minimal in cost and, along with the fencing, may prevent many animal-vehicle collisions per year.

Wildlife Crossing Design Elements

Figure 6 illustrates various forms of wildlife crossings, ranging from large overpasses to small drainage culverts. For a detailed description and detailed illustrations of crossing types and design considerations, the reader may refer to Iuell et al. (2003), and various websites including the Wildlife Crossings Toolkit (USDA Forest Service, 2005); Critter Crossings (Federal Highway Administration, 2006), and Wildlife and Roads (developed as a result of NCHRP 25-27 [Bissonette et al., n.d.]).
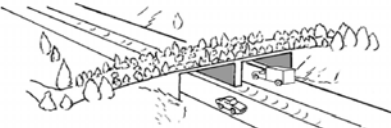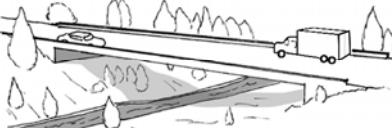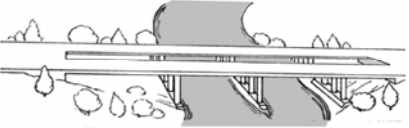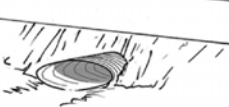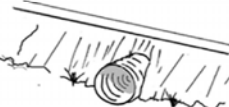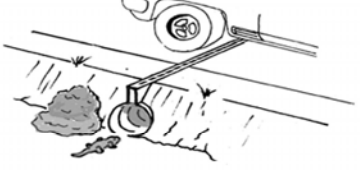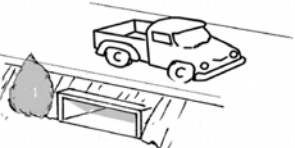
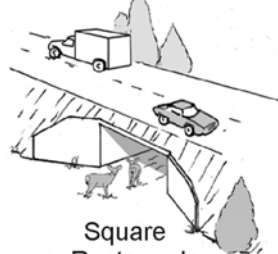| Overpass	
Underpasses	
Bridges	Single-span Multiple-span Viaduct
Pipes	Elliptical Circular Arch Slotted Drain
Box Culverts	Square or Rectangular Multiple Chamber
Bottomless Pipes	Arch Square or Rectangular

Figure 6. Types of Wildlife Crossings. Illustration credit: USDA Forest Service, Wildlife Crossings Toolkit. Accessible at http://www.wildlifecrossings.info/. Used with permission.

Number and Spacing

The appropriate number and spacing intervals for effective wildlife crossings along a particular road segment is an area that requires additional research. Depending on the circumstances, one or more large passages may be appropriate, whereas other situations may be best suited for a larger number of smaller structures. If particular species are targeted for wildlife crossing use, the number and placement of crossing structures should depend on the species' behavior and distribution in the area. To obtain high passage rates for a variety of species, frequently spaced crossing structures (490 to 980 ft) of varying sizes have been recommended (Clevenger and Waltho, 1999, 2005). Smith (2003) found that a maximum distance of 660 to 820 ft between structures was necessary to sustain 90% passage for most species, including deer. A variety of considerations are involved in these decisions beyond species preferences, however, including cost, aesthetics, and surrounding land use.

Types and Dimensions

Effective wildlife crossings come in various designs and sizes, including small corrugated drainage pipes, box culverts, arch or elliptical culverts, and large bridges (Figure 6). In general, areas of high conservation priority may require more extensive (and often more costly) measures. The construction of larger wildlife crossings, such as bridges or large culverts, would accommodate a larger variety of wildlife and would potentially facilitate movement for more individuals. In areas with a medium or low conservation priority, it may be more suitable to construct passages with medium dimensions or to modify existing structures to encourage wildlife use.

The decision of whether or not to design a structure for a target species is often determined by the specific context and project location. Some encourage designing a structure with the objective of connecting habitats at an ecosystem level (for a multitude of species) rather than targeting a particular species (Van der Grift and Pouwels, 2006). Wildlife overpasses and large bridges are the most likely designs to accomplish this, but this approach may not be feasible and affordable for most situations. For cost purposes, transportation agencies are often interested in the smallest size dimensions that will accommodate a particular species. Providing appropriate size dimensions is only one of several factors that determine the effectiveness of a crossing, and dimensions that prove effective in some areas may not be effective in others. Although more research in this area in needed, studies have provided recommendations that are likely to be useful in crossing design.

Design Considerations for Large and Medium-Sized Mammals. DVCs pose a large threat to driver safety and are associated with high property damage costs (Hedlund et al., 2003). Based on the success of wildlife crossings at reducing DVCs (Clevenger et al., 2002; Donaldson, 2005), these structures should be a more commonly considered strategy to mitigate this problem. Bridges and wildlife overpasses can be highly successful at facilitating deer passage and they provide multiple benefits beyond deer passage alone, but their size and cost may be greater than what is necessary for targeting deer. For less expensive structures such as culverts, less is known regarding the minimum size dimensions necessary to facilitate white-tailed deer passage. The same

is true for black bears, which are also a threat to driver safety and depend on long-range movement to sustain their populations.

Table 2 lists culverts used by white-tailed deer and black bears that were smaller and less costly than a typical bridge. As may be seen, large culverts can be relatively inexpensive (as compared to a bridge that can cost more than $1 million) and can serve the dual purposes of wildlife and water passage (if the drainage is channeled such that dry land is provided in the structure). Of the underpasses studied in Virginia, structures large enough to be successful in terms of deer passage were also heavily used by a variety of other wildlife species (Donaldson, 2005).

The "openness" of a structure, calculated by [(height x width)/length], has also been found to be a significant factor in determining the relative effectiveness of structures in terms of use by deer and other species (Reed et al., 1975). Openness is largely a measure of ambient light in the passage; the larger the openness value, the less of a narrow and "tunnel-like" appearance of the structure. For deer in Virginia, a combination of structural dimensions such that the openness value is greater than 0.19 (using metric measurements) is recommended (Donaldson, 2005).

Structures large enough to facilitate deer passage have also been found to be heavily used by a variety of medium-sized wildlife species, including fox, coyote, bobcat, raccoon, opossum, groundhog, and various reptile and amphibian species. Medium-sized species have been found to use box culverts with openings of 10 x 6 x 105 ft and 6 x 6 x 58 ft (Donaldson, 2005). Many of these species are also likely to use smaller structures (Iuell et al., 2003). As with all

Table 2. Attributes, or Recommended Minimum Attributes Based on Authors' Conclusions, of Culverts Used by (or Proposed for) White-Tailed Deer and Black Bear

Culvert	Deer/ Bear	Width (ft)	Height (ft)	Length (ft)	Fencing (ft)	Cost[a]	Location	Source
Bottomless box (concrete)	Deer	20	15	192	None	$260,000	Virginia	Donaldson (2005)
Box (concrete)	Deer	10[b]	12	189	None	$690,000	Virginia	Donaldson (2005)
Bottomless box	Both	11.5[c]	9.8[c]	-	NA	NA	Florida	Smith (2003)
Bottomless box	Both	25	8	47	5,800	$870,000	Florida	Land and Lotz (1996)
Corrugated steel	Deer	12.1	7.5	90.6	None	NA	Montana	Foresman (2004)
Corrugated steel	Deer	11.5	12.3	213.3	None	NA	Montana	Foresman (2004)
Elliptical metal	Both	23.0	13.1	NA	NA	$150,000-$170,000	Alberta, Canada	Foreman et al. (2003)
Corrugated metal pipe bottomless arch; proposed	Deer	24	12	178.6	NA	$150,000	Colorado	Colorado DOT and FHWA (2001)

[a]Approximate cost of unit. Some costs (not specified in literature) include materials cost.
[b]Although this structure received heavy use by deer, the author recommends a wider opening to discourage the high number of hesitation and turn-arounds deer exhibited during a monitoring study.
[c]Recommended minimum size based on study conclusions.

structures, however, adequate size dimensions alone are not sufficient to guarantee the effectiveness of a structure.

Design Considerations for Small Species. For small species such as reptiles, amphibians, and small mammals, successful structures range from common drainage structures (corrugated pipes) to small box culverts. Rectangular structures with widths of 2 to 4 ft have been found to accommodate a variety of small species such as amphibians, which will use the side as a guide (O'Brien, 2006; Jackson, 1996). Because some species avoid metal or concrete, structure floors should be covered with soil or another natural substrate (Iuell et al., 2003).

As with any crossing structure, the behavior and physiology of the species should be considered. Amphibians, for instance, are sensitive to drying out and may therefore require a drainage channel through the structure (Iuell et al., 2003). Slotted drains (Figure 6) or grating (Jackson, 1996) can be an effective way to allow moisture into a pipe. Small mammals, however, may not travel through a wet culvert and may require a small shelf installed along the length of the interior culvert (Foresman, 2004; Figure 5).

Carefully fit guiding structures, such as short fencing or concrete barriers, are necessary on both sides of the structure, parallel with the road. To prevent animals from climbing the fence, fencing material should not be made of wire mesh or netting. For amphibians, the recommended height for fencing is 16 to 24 in (Iuell et al., 2003), or a minimum of 12 in for salamanders specifically (Jackson, 1996). The fence should be curved away from the road at both ends to prevent the animal from traveling away from the structure (Iuell et al., 2003).

Fish Passage. Research is becoming increasingly available on fish passage design, and the requirements are specific depending on the species. Proper designs of fish passage structures are beyond the scope of the general guidelines in this report, and experts should be consulted prior to passage design.

Fencing and Escape Structures

Fencing extending from wildlife crossing openings has been shown to increase greatly the effectiveness of crossings (Clevenger et al., 2001). The addition of fencing to crossing structures along a Wyoming interstate also significantly reduced DVCs (Ward, 1982). Although studies do not provide clear guidance on fencing lengths, chain link fences that are 10 ft high and 1.1 mi long have effectively funneled deer and black bear through an underpass in Florida (Roof and Wooding, 1996). Deer fencing should have a height of 8 to 10 ft to prevent deer from entering the roadway. Gallagher et al. (2003), however, found that deer stopped using an established feeding area when faced with a 5.5-ft fence constructed of burlap, presumably because they were reluctant to cross a barrier that obstructed their view of the opposite side.

Escape structures are important components along a fence to prevent wildlife from becoming trapped in the roadway. Escape ramps (Figure 7) appear to be the most effective structures among those available (including one-way gates and funnel fences) (T. Brennan, personal communication, 2006). Ramps are generally designed for deer or other ungulates such that an animal trapped between fencing in the right of way can jump off the ramp but not be

Figure 7. Escape Ramp on Arizona State Route 260. Photo credit: Terry Brennan, Tonto National Forest. Used with permission.

likely to jump up onto the ramp. The Arizona DOT constructed a series of escape ramps 5 to 7 ft high and one-way gates along a fence 8 ft high between underpass structures on S.R. 260 (Brown et al., 1999).

Vegetation, Substrate, and Approach

Designing the immediate surroundings and underpass floor to mimic the natural habitat of the area as closely as possible will encourage use. Vegetation leading up to the structure entrances serves as cover, and continuity of the natural habitat on both sides of the structure provides a less intimidating approach to the structure entrances (Servheen, 2003). Although open-bottom structures are optimal, concrete or metal floors can be covered with natural substrate such as dirt and rocks. Rocks of varying sizes placed along a culvert can also serve as cover for small species. For larger box culverts that also serve as drainage structures, mimicking a natural stream along a portion of the culvert can encourage use by a variety of wildlife. Approaches to the structure should be as level as possible and should be free from obstacles that may impede movement or obstruct the view of the structure entrance and exit (Iuell et al., 2003).

Maintenance

Maintenance of wildlife crossings is essential to ensure long-term functionality and to encourage regular wildlife use. The entrances should be kept free of debris, and vegetation should be maintained and prevented from obstructing the view of and access to the entrances. Care should be taken to ensure that culverts do not flood or support standing water (Iuell et al., 2003). Regular maintenance of fencing is necessary to prevent wildlife from breaking through damaged sections (Bashore et al., 1985).

Variables That Influence Road-Crossing Attempts

Characteristics of road traffic should be considered when assessing the need for mitigation. Traffic intensity and vehicle speed are particularly important factors in predicting the effects of a road project on wildlife movement and animal-vehicle collisions. Although on a broad scale, collision numbers increase linearly with traffic volume; at a local level, this effect is confounded by animal behavior, road characteristics, and temporal and landscape factors. At a certain traffic volume, road crossing attempts (and therefore road mortality) decrease because of the barrier effect of heavy traffic. During periods of heavy traffic, animals are more likely to avoid the movement or loud noise of vehicles (Seiler and Helldin, 2006).

Models have attempted to predict the probability of successful animal crossings given variables such as traffic volume and speed, road width, animal speed and length, and movement behavior. Traffic volume and animal traversing speed were found to have the largest effect on traffic mortality in one study (Van Langevelde and Jaarsma, 2004). Formula and model results vary regarding the critical threshold for the traffic volume that will prevent attempted and successful crossings. A model partly based on moose-vehicle collisions found that at a traffic volume of approximately 5,000 vehicles per average day, the number of animals killed on a road decreases and the number of animals repelled from the road increases. Muller and Berthoud (1997) found that highways with traffic volumes greater than 10,000 per day are considered an impenetrable barrier to most terrestrial animals.

CONCLUSIONS

- *Wildlife crossings with fencing are effective at connecting animal habitat and reducing animal-vehicle collisions.* Effective structures for deer and other wildlife in Virginia can cost less than $300,000. Costs for these structures can be minimized by modifying existing bridges or culverts to accommodate wildlife passage.

- *Several mitigation measures are likely to be effective at reducing animal-vehicle collisions but require additional research before a conclusion regarding their effectiveness can be drawn.*

    — active signs and technologies
    — roadside clearing

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— deicing salt alternatives
— roadway design and planning policies
— public information and education
— in-vehicle technologies
— herd reduction.

Dynamic message signs and animal-detection driver warning systems (active signs and technologies), in particular, hold promise in slowing driver speed and increasing awareness. Applying roadway design and planning practices to avoid certain high animal movement areas or to implement mitigation in those areas is also likely effective at reducing accidents.

- *Certain other measures appear ineffective or have limited effectiveness:*

  — speed limit reduction
  — passive deer crossing signs
  — roadway lighting
  — intercept feeding
  — deer repellents.

- *Some measures have been shown to be ineffective:*

  — deer whistles
  — deer flagging models
  — roadside reflectors.

- *Animal-vehicle collisions are more likely to occur where wildlife corridors intersect with roads.* Avoiding corridors identified by the Virginia Department of Conservation and Recreation's GIS landscape corridor analysis (VANLA) or applying effective mitigation measures may decrease the risk of collisions in these areas (Donaldson and Weber, 2006).

- *Variables such as traffic intensity and vehicle speed are important considerations in predicting the impacts of a road project on animal movement and animal-vehicle collisions.*

COSTS AND BENEFITS ASSESSMENT

Cost is often the largest deterrent to the implementation of methods to reduce animal-vehicle collisions or provide habitat connectivity for wildlife. Decisions to apply mitigation are often based on a transportation agency's expected return on investment, which can seem an obscure and difficult value to predict. Although there are numerous benefits to making roads safer for wildlife, these benefits are often placed in the category of "environmental stewardship" rather than being discussed in terms of their monetary benefits. The financial benefits to mitigation are important considerations, however, as they can affect the driving public in terms of safety, time lost to traffic delays, and the value placed on wildlife. Transportation agencies also incur tremendous costs associated with carcass removal and disposal, as well as worker

safety issues from handling carcasses. The ability to quantify the monetary value of mitigation can be especially useful for a transportation agency in justifying its decisions regarding implementation. This value will also be of interest to the public and various organizations.

Cost of Mitigation Versus Benefits in Property Damage Savings

One approach to a cost-benefit analysis that can be useful to a transportation agency involves quantifying the benefits in terms of driver safety. Driver safety includes a reduction in animal-vehicle collisions and the corresponding decrease in property damage, which translates into savings for taxpayers. Donaldson (2005) calculated the annualized cost of successful wildlife crossings and compared those values to the annual savings in property damage from the corresponding reduction in DVCs.

The annualized cost, or the yearly cost of mitigation as if it were uniform throughout its service life, can be calculated for any form of mitigation for comparison with the yearly average property costs from animal-vehicle collision incidents. In Virginia in 2003, for example, the average cost in property damage from a reported DVC was $2,530.

The annualized cost (AC) for mitigation can be calculated by the formula

$$AC = CR/1 - (1 + R)^{-T}$$

where

C = cost for the mitigation, including maintenance costs
R = interest rate (generally estimated at 0.05)
T = service life of the mitigation.

Using the example from Donaldson (2005), the annualized cost of the least expensive, heavily used wildlife crossing from the study was calculated to be $6,600 (for a box culvert with a 10 x 12 ft opening). At an average property damage cost of $2,530 for a reported DVC, more than 2.6 (or $6,600 ÷ $2,530) DVC reductions per year would be required in order for the savings in property damage to be greater than the cost of the wildlife crossing. Considering that there were 319 deer crossings through this structure in 1 year, it is likely that more than 2.6 DVCs were prevented that year. If so, the benefits of the structure outweighed the costs in property damage savings alone. Although the actual number of DVC reductions resulting from a form of mitigation may be unknown (as it was in this example), this calculation provides tangible information on which to base informed judgments regarding mitigation decisions.

Costs of Mitigation Versus Benefits Using Multiple Parameters

Although analyzing the costs of a collision in terms of property damage alone is one simple and straightforward approach, many other considerations can factor into these costs. A cost-benefit analysis conducted by the Utah DOT included the value of a wild animal (using

hunting-related expenses and the number of harvested animals) and the delay cost to the traveling public (Page, 2006).

Another analysis incorporated property damage costs, costs associated with human injuries and fatalities, the monetary value of the animal killed in the collisions, and the carcass disposal costs (Huijser et al., 2006). These costs were compared to the costs of the mitigation (in this case, an animal-detection driver warning system). The yearly costs of the mitigation method were estimated at $31,300, given a 10-year lifespan. This analysis concluded that the benefits of the system outweighed the costs at locations reporting as few as five DVCs per mile road length per year.

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REFERENCES

Austin, J.M., Viani, K., Hammond, F., and Slesar, C. A GIS-Based Identification of Potentially Significant Wildlife Habitats Associated with Roads in Vermont. In *Proceedings of the International Conference on Ecology and Transportation*, C. L. Irvin, P. Garrett, and K.P. McDermott, eds. Center for Transportation and the Environment, North Carolina State University, Raleigh, 2006.

Bashore, T., Tzilkowski, W.M., and Bellis, E.D. Analysis of Deer-Vehicle Collision Sites in Pennsylvania. *Journal of Wildlife Management*, Vol. 49, No. 3, 1985, pp. 769-774.

Bissonette, J.A. et al. Wildlife and Roads: A Resource for Helping to Mitigate Roads for Wildlife, n.d. http://www.wildlifeandroads.org/. Accessed November 16, 2006.

Brown, D.L., Laird, J., Sommers, W.D., and Hamilton, A. Methods Used by the Arizona Department of Transportation to Reduce Wildlife Mortality and Improve Highway Safety. In *Proceedings of the Third International Conference on Wildlife Ecology and Transportation*, G.L. Evink, P. Garrett, and D. Zeigler, eds. FL-ER-73-99. Florida Department of Transportation, Tallahassee, 1999, pp. 181-182.

Bruinderink, G., and Hazebroek, E. Ungulate Traffic Collisions in Europe. *Conservation Biology*, Vol. 10, No. 4, August 1996, pp. 1059-1067.

Cain, A.T., Tuovila, V.R., Hewitt, D.G., and Tewes, M.E. Effects of Highway and Mitigation Projects on Bobcats in Southern Texas. *Biological Conservation*, Vol. 114, 2003, pp. 189-197.

Clevenger, A.P., and Waltho, N. Dry Drainage Culvert Use and Design Considerations for Small and Medium-sized Mammal Movement Across a Major Transportation Corridor. In *Proceedings of the Third International Conference on Wildlife Ecology and Transportation,* G.L. Evink, P. Garrett, and D. Zeigler, eds. FL-ER-73-99. Florida Department of Transportation, Tallahassee, 1999, pp. 263-277.

Clevenger, A.P., and Waltho, N. Performance Indices to Identify Attributes of Highway Crossing Structures Facilitating Movement of Large Mammals. *Conservation Biology*, Vol. 121, 2005, pp. 453-464.

Clevenger, A.P., Chruszcz, B., and Gunson, K. Highway Mitigation Fencing Reduces Wildlife-Vehicle Collisions. *Wildlife Society Bulletin*, Vol. 29, 2001, pp. 646-653.

Clevenger A., Chruszcz, B., Gunson, K., and Wierzchowski, J. *Roads and Wildlife in the Canadian Rocky Mountain Parks: Movements, Mortality and Mitigation.* Final Report to Parks Canada. Banff, Alberta, Canada, 2002.

Colorado Department of Transportation and Federal Highway Administration. *South I-25 Corridor and US 85 Corridor Final Environmental Impact Statement (May 2001) and Record of Decision.* Prepared by PBS&J. Denver, 2001.

D'Angelo, G.J. Ineffectiveness of Wildlife Warning Reflectors for Altering White-tailed Deer Behavior Along Roadways. *Wildlife Society Bulletin*, in press, 2006.

Donaldson, B.M. *The Use of Highway Underpasses by Large Mammals in Virginia and Factors Influencing Their Effectiveness.* VTRC 06-R2. Virginia Transportation Research Council, Charlottesville, 2005.

Donaldson, B.M., and Weber, J.T. *Use of a GIS-Based Model of Habitat Cores and Landscape Corridors for Transportation Project Planning and Environmental Scoping by the Virginia Department of Transportation.* VTRC 07-R14. Virginia Transportation Research Council, Charlottesville, 2006.

Federal Highway Administration. Critter Crossings: Linking Habitats and Reducing Roadkill, 2003. http://www.fhwa.dot.gov/environment/wildlifecrossings/. Accessed August 10, 2006.

Finder, R.A., Roseberry, J.L., and Woolf, A. Site and Landscape Conditions at White-tailed Deer/vehicle Collision Locations in Illinois. *Landscape and Urban Planning*, Vol. 44, 1999, pp. 77-85.

Forman, R.T.T. *Land Mosaics: The Ecology of Landscapes and Regions*. Cambridge University Press, New York, 1995.

Forman, R.T.T., Sperling, D., Bissonette, J., Clevenger, A., Cutshall, C., Dale, V., Fahrig, L., France, R., Goldman, C., Heanue, K., Jones, J., Swanson, F., Turrentine, T., and Winter, T.C. *Road Ecology: Science and Solutions*. Island Press, Washington, DC, 2003.

Foresman, K.R. *The Effects of Highways on Fragmentation of Small Mammal Populations and Modifications of Crossing Structures to Mitigate Such Impacts*. FHWA/MT-04-005/8161. Montana Department of Transportation, Helena, 2004.

Gallagher, G.R., Keen, H.A., and Prince, R.H. Effectiveness of a Perceived Solid Barrier as an Exclusion Fence to Prevent White-Tailed Deer Damage. In *Proceedings of the Tenth Wildlife Damage Management Conference,* K.A. Fagerstone and G.W. Witmer, eds. National Wildlife Research Center, Fort Collins, CO, 2003, pp. 23-28.

Gunther, K.A., Biel, M.J., and Robison, H.L. Factors Influencing the Frequency of Road-killed Wildlife in Yellowstone National Park. In *Proceedings of the International Conference on Wildlife Ecology and Transportation*, Fort Myers, FL, February 9-12, 1998, pp. 395 to 405.

Hardy, A., Fuller, J., Lee, S., Stanley, L., and Al-Kaisy, A. *Bozeman Pass Wildlife Channelization ITS Project.* Report 425539. Montana Department of Transportation, Helena, 2006.

Hedlund, J.H., Curtis, P.D., Curtis, G., and Williams, A.F. *Methods to Reduce Traffic Crashes Involving Deer: What Works and What Does Not*. Insurance Institute for Highway Safety, Arlington, VA, 2003.

Hubbard, M.W., Danielson, B.J., and Schmitz, R.A. Factors Influencing the Location of Deer-vehicle Accidents in Iowa. *Journal of Wildlife Management*, Vol. 64, 2000, pp. 707-713.

Huijser, M., McGowen, P., Camel, W., Hardy, A., Wright, P., and Clevenger, A. *Animal Vehicle Crash Mitigation Using Advanced Technology, Phase I: Review, Design, and Implementation.* FHWA-OR-TPF-07-01. Oregon Department of Transportation, Salem, 2006.

Iuell, B., Bekker, G.J., Cuperus, R., Dufek, J., Fry, G., Hicks, C., Hlavac, V., Iuell, V., Rosell, C., Sangwine, T., Torslov, N., and Wandall, B.M., eds. *Wildlife and Traffic: A European Handbook for Identifying Conflicts and Designing Solutions*. KNNV Natural History Publishers, Utrecht, The Netherlands, 2003.

Jackson, S.D. Underpass Systems for Amphibians. In *Trends in Addressing Wildlife Mortality: Proceedings of the Transportation Related Wildlife Mortality Seminar,* G.L.

Evink, P. Garrett, D. Zeigler, and J. Berry, eds. FL-ER-58-96. Florida Department of Transportation, Tallahassee, 1996.

Knapp, K.K., Yi, X., Oakasa, T., Thimm, W., Hudson, E., and Rathmann, C. *Deer Vehicle Crash Countermeasure Toolbox: A Decision and Choice Resource.* Report DVCIC-02. Wisconsin Department of Transportation, Madison, 2004.

Land, D., and Lotz, M. Wildlife Crossing Designs and Use by Florida Panthers and Other Wildlife in Southwest Florida. In *Trends in Addressing Wildlife Mortality: Proceedings of the Transportation Related Wildlife Mortality Seminar,* G.L. Evink, P. Garrett, D. Zeigler, and J. Berry, eds. FL-ER-58-96. Florida Department of Transportation, Tallahassee, 1996, pp. 379-386.

Metropolitan Washington Council of Governments. *The Wildlife-Vehicle Reduction Avoidance Policy Statement and Report.* Washington, DC, 2006.

Meyer, E. *Assessing the Effectiveness of Deer Warning Signs.* Report K-TRAN: KU-03-6. Kansas Department of Transportation, Topeka, 2006.

Muller, S., and Berthoud, G. *Fauna/Traffic Safety: Manual for Civil Engineers.* LAVOC, Lausanne, Switzerland, 1997.

O'Brien, E. Habitat Fragmentation Due to Transport Infrastructure: Practical Considerations. In *The Ecology of Transportation: Managing Mobility for the Environment,* J. Davenport and J.L. Davenport, eds. Dordrecht, The Netherlands, 2006.

Page, M. Wildlife and Domestic Animal-Vehicle Collisions in Utah. Paper presented at the 85th Annual Meeting of the Transportation Research Board, Washington, DC, January 2006.

Parks Canada. Highway Mitigation Research in the Mountain Parks. Gatineau, Quebec, 2004. http://www.pc.gc.ca/pn-np/ab/banff/docs/routes/chap3/sec4/routes3d_e.asp/. Accessed August 3, 2006.

Reed, D.F., Woodward, T.N., and Pojar, T.M. Behavioral Response of Mule Deer to a Highway Underpass. *Journal of Wildlife Management*, Vol. 39, 1975, pp. 361-167.

Romin, L.A. *Factors Associated with the Highway Mortality of Mule Deer at Jordanelle Reservoir, Utah.* Master's Thesis, Utah State University, Logan, 1994.

Roof, J., and Wooding, J. Evaluation of the S.R. 46 Wildlife Crossing in Lake County, Florida. In *Trends in Addressing Wildlife Mortality: Proceedings of the Transportation Related Wildlife Mortality Seminar,* G.L. Evink, P. Garrett, D. Zeigler and J. Berry, eds. FL-ER-58-96. Florida Department of Transportation, Tallahassee, 1996.

Schaefer, J.M., and Smith, D.J. *Ecological Characterization of Identified High Priority Highway-Ecological Interface Zones Including the Inventory and Evaluation of Existing*

Florida Department of Transportation Highway Facilities Within These Zones. Florida
Department of Transportation, Tallahassee, 2000.

Seiler, A., and Helldin, J.O. Mortality in Wildlife Due to Transportation. In *The Ecology of
Transportation: Managing Mobility for the Environment*, J. Davenport and J.L.
Davenport, eds. Dordrecht, The Netherlands, 2006.

Servheen, C. A Sampling of Wildlife Use in Relation to Structure Variables for Bridges and
Culverts Under I-90. In *2003 Proceedings of the International Conference on Ecology
and Transportation,* C.L. Irwin, P. Garrett, and K.P. McDermott, eds. Center for
Transportation and the Environment, North Carolina State University, Raleigh, 2003, pp.
331-341.

Singleton, P.H., and Lehmkuhl, G.F. Assessing Habitat Connectivity in the Interstate 90
Snoqualmie Pass Corridor, Washington. In *Proceedings of the International
Conference on Ecology and Transportation*, C.L. Irvin, P. Garrett, and K.P. McDermott,
eds. Center for Transportation and the Environment, North Carolina State University,
Raleigh, 2006.

Smith, D.J. *Monitoring Wildlife Use and Determining Standards for Culvert Design.* BC354-
34. Florida Department of Transportation, Tallahassee, 2003.

USDA Forest Service. *Wildlife Crossings Toolkit,* 2005. www.wildlifecrossings.info. Accessed
August 10, 2006.

Van der Grift, E., and Pouwels, R. Restoring Habitat Connectivity Across Transport Corridors:
Identifying High-Priority Locations for De-fragmentation with the Use of an Expert-
based Model. In *The Ecology of Transportation: Managing Mobility for the
Environment*, J. Davenport and J.L. Davenport, eds. Dordrecht, The Netherlands, 2006.

Van Langevelde, F., and Jaarsma, C.F. Using Traffic Flow Theory to Model Traffic Mortality in
Mammals. *Landscape Ecology*, Vol. 19, No. 8, 2004, pp. 895-907.

Virginia Department of Game and Inland Fisheries. What Can I Do to Avoid Hitting a Deer with
My Car? 2006. http://www.dgif.state.va.us/wildlife/deer/faq.asp#avoid-hitting-deer.
Accessed September 15, 2006.

Ward, A.L. Mule Deer Behavior in Relation to Fencing and Underpasses on Interstate 80 in
Wyoming. In *Transportation Research Record 859.* Transportation Research Board,
Washington, DC, 1982, pp. 8-13.