Recommendations of Road Passage Designs for Jaguars

A Final Submission to the U.S. Fish and Wildlife Service in Partial Fulfillment of Contract F14PX00340

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Executive Summary

Transportation networks fragment the natural landscape and create barriers that interfere with animals' ability to move across landscapes to meet biological needs such as finding food, water, cover, and dispersing to new areas to secure access to mates to increase genetic diversity. Mortality of wildlife due to collisions with vehicles can have direct impacts at the population level; for example, road mortality is among the major threats to the survival of 21 endangered or threatened species in the U.S. (Huijser et al. 2008). For many imperiled or sensitive species, the impacts of roads may be uncertain. The U.S. Fish and Wildlife Service (2012) Recovery Outline for the jaguar (*Panthera onca*) identified the need to assess the impact of roads on jaguars and measures to enable these rare carnivores to safely cross roads for the recovery of this species. This document addresses these measures by offering recommendations drawn from a growing body of literature and case studies on techniques that have high potential to facilitate safe movements of jaguar across roads at the northern extent of their historical range in Mexico and in the southwest United States (i.e., the Northwestern Recovery Unit).

The impacts of roads and traffic on wildlife may be reduced via three primary approaches: manipulating driver behaviors, manipulating animal behaviors, or physically separating wildlife from traffic on roadways. The latter techniques, applied by using wildlife crossing structures and associated fencing to guide animals to passages over or under roads, have proven to be most successful in reducing wildlife-vehicle collisions while allowing animals to move across the landscape.

This report provides broad recommendations for enhancements that may increase the likelihood of safe passage of jaguars across roads in a variety of different habitat types in the Northwestern Recovery Unit (Figure 1). This report follows from our review of enhancements, including efforts to modify driver and animal behavior and physical structures to channel wildlife movements safely under/over road corridors (Matthews et al. 2014). Given these structures are largely absent for jaguars, specifically, or unstudied throughout the jaguar's range, our recommendations are based on literature that addresses the most appropriate surrogate taxonomic group or species, in most cases large carnivores, generally, or pumas (*Puma concolor*), specifically.

Pumas, other large carnivores, and their prey exhibit species-specific tendencies in their use of overpasses and underpasses. We recommend large overpasses and underpasses for the passage of jaguars and their prey with fencing to guide animals to the crossing structures and prevent animals from climbing over or digging under the fencing. These structures are anticipated to be most effective if they are designed and built wide enough with berms on the edges (in the case of overpasses) to prevent individual animals from seeing traffic below them. Further, we suggest that the surrounding environment leading to these structures have suitable levels of concealment cover; are suitable distances away from development, human activity, and artificial light sources; and are built to provide an unobstructed view of the habitat on the far side of the structure. In

addition to modeling techniques and expert opinion to broadly identify where these passages are most likely to be used by jaguar and their prey, localized assessments of the landscape context and human activity, coupled with monitoring of wildlife movements pre- and post-construction, are key elements in selecting optimal crossing structure locations and evaluating their success.

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Introduction

Maintaining connectivity for jaguars from southern Arizona and New Mexico south through the Sierra Madre Occidental of Mexico is of significant conservation concern (Zeller 2007, Rabinowitz and Zeller 2010, U.S. Fish and Wildlife Service 2012). Studies of genetic variation among jaguars have shown little evidence of significant geographical partitions and barriers to gene flow range wide (Eizirik et al. 2001, Johnson et al. 2002, Ruiz-García et al. 2009). Given this, and the demographic benefits of connectivity, maintaining connectivity between jaguar breeding areas is a vital component in conservation planning for the species (Rabinowitz and Zeller 2010).

Roads and associated traffic can disrupt connectivity and detrimentally affect wildlife populations in four ways: 1) decrease habitat amount, availability, and quality; 2) increase mortality due to collisions with vehicles; 3) limit movements and access to resources within and beyond ranges; and 4) fragment habitat and wildlife populations into smaller and more vulnerable subpopulations (Maehr 1997, Forman and Alexander 1998, Smith 1999, Forman et al. 2003, Mills and Conrey 2003, Jaeger et al. 2005, Riley et al. 2006, Strasburg 2006). Habitat loss can be direct, in the form of habitat removal when roads are built. Habitat loss can also be indirect, where habitat quality close to roads is diminished due to noise, light, pollutants, or other road-associated impacts. Increased mortality rates due to collisions between vehicles and wildlife can compromise population persistence, if higher birth rates do not compensate for increased mortality, and disrupt social structures, especially for large territorial felids (Fuller 1989, Ferreras et al. 1992, van der Zee et al. 1992). For some species, noise and visual movement of vehicles on roads can restrict movement and access to resources, including food, mates, and breeding sites. These barriers to movements and dispersal behaviors, and reduced access to resources, can lead to lower reproductive and survival rates (Brody and Pelton 1989, Reijnen and Foppen 1994, Ortega and Capen 1999, Forman et al. 2003, Beckmann et al. 2010), higher population subdivision by restricting flow of individuals and genetic material between subpopulations, and, thus, threaten population persistence (Swihart and Slade 1984, Noss et al. 1996, Gerlach and Musolf 2000).

Throughout the range of the jaguar, generally, and within the Northwestern Recovery Unit of the jaguar (NRU; Figure 1), specifically, more information is needed about the impact of roads upon jaguar movement and the effectiveness of under- and overpasses and other design measures to facilitate jaguar travel across these roads or highways (U.S. Fish and Wildlife Service 2012). To increase the long-term survival of jaguar subpopulations, maintaining and improving (when necessary) connectivity for movement of jaguars throughout the landscape and between populations is recommended, and using road crossing enhancements that decrease the risk of mortality associated with roads and facilitate jaguar movement across roads is encouraged (U.S. Fish and Wildlife Service 2012).

This report provides broad recommendations for enhancements that may increase the likelihood of safe passage of jaguars across road infrastructure in a variety of different habitat types in the NRU (Figure 1). These recommendations follow from our review of enhancements to reduce wildlife-transportation conflicts, including efforts to modify driver and animal behavior and physical structures to channel wildlife movements safely under/over roadways (Matthews et al. 2014). These recommendations will be followed by a report identifying potential areas where enhancements would improve the passage of jaguars across different types of road corridors that would be effective in a variety of different habitat types (Stoner et al. 2014). Given the paucity of jaguar-specific examples from which we can infer, our recommendations are based heavily on literature that addresses similar large felids, such as pumas (*Puma concolor*), and other carnivores with the assumption that these animals may respond to roads and wildlife crossings similarly.

Enhancements to Modify Driver Behavior

Mitigation measures aimed at influencing driver behavior have met with mixed success (Huijser et al. 2008, Huijser and McGowen 2010). These measures range from public information and education, to various types of permanent warning signs, seasonal warning signs, animal detection systems that warn drivers of wildlife on the roadway in real-time, and measures that increase the visibility for drivers. Permanently visible wildlife warning signs and enhanced wildlife warning signs (e.g., signs with flashing lights and additional flagging, dynamic message signs) have not been shown to significantly reduce the number of wildlife-vehicle collisions (Pojar et al. 1975, Rogers 2004, Meyer 2006, Stanley et al. 2006).

In contrast to static wildlife warning signs, we recommend further investigation into the use of road-based animal detection-driver warning systems. These systems use sensors to detect large animals that approach the road and correspondingly activate dynamic warning signs indicating drivers should watch for wildlife crossing at that time. The effectiveness of reliable animal detection systems in reducing collisions with large ungulates has been estimated at 82% (Mosler-Berger and Romer 2003) and 91% (Dodd and Gagnon 2008) in certain conditions and settings. However, depending on the type of detection technology used (e.g., microwave, radar, break-the-beam systems), detection probabilities are potentially higher for larger animals such as ungulates than smaller animals (Huijser et al. 2009). The reliability of these types of systems for large carnivores is generally unknown, although success rates may be lower for carnivores in comparison to ungulates because of their smaller body size, an idea that warrants further investigation (Huijser et al. 2009). Further, road-based animal detection systems are more effective in detecting the presence of animals in more open habitats and less likely to incur false positive detections that can erode drivers trust in the system, issues to consider given the wide range of habitats occupied by jaguars, especially dense tropical vegetation in the neo-tropic regions of the western hemisphere. Huijser et al. (2009:22) describe characteristics and reliability of 9 animal detection systems and associated equipment costs ranging between $260 and $17,300 for a system at a single location.

Huijser and McGowen (2010) acknowledge there are several advantages to animal detection systems compared to wildlife crossing structures, including: 1) detection systems have the potential to provide wildlife with safe crossing opportunities anywhere along roadways deemed appropriate for these systems; 2) they are less restrictive to wildlife movement than fencing or crossing structures; 3) they can be installed without major road construction or traffic control for long periods; and 4) they are likely to be less expensive than wildlife crossing structures. Disadvantages of animal detection systems are unreliability and somewhat sporadic behavior at the present time (e.g., during storms or high wind events that give "false animal detection"), although these issues are improving with more research on and development of these systems (Huijser et al. 2009).

Enhancements to Modify Animal Behavior

There are two basic approaches to modifying animal behavior to reduce traffic impacts on wildlife: 1) deter wildlife from approaching roads, or 2) direct wildlife movements to places to cross roads safely. Deterring wildlife from approaching roads has the potential to reduce wildlife-vehicle collisions, but has negative consequences associated with limiting wildlife movements across landscapes to meet biological needs; thus, we do not recommend using barriers to restrict wildlife access to roads without providing means for wildlife to cross roads. More appropriate for the conservation of wide-ranging, threatened and endangered species are measures that modify wildlife behavior to direct their movements using physical barriers such as fencing to separate animals from traffic while providing opportunities for wildlife to cross via conduits under and over roadways. Recommendations on these measures for jaguar safe passage are detailed throughout subsequent sections.

Enhancements to Direct Jaguars Safely Under/Over Roads

Wildlife crossing structures are a relatively new application of transportation infrastructure that offer safe crossing opportunities for wildlife, thereby connecting habitats and wildlife populations, reducing wildlife mortality on roads, and increasing motorist safety. Wildlife crossing and infrastructure designs require thoughtful assessment of species-specific behaviors that can influence the effectiveness of these infrastructure investments. Wildlife use of crossing structures depends on several factors, including location on the landscape, distance between structures, habitat surrounding the structures, dimensions of the structure, presence or absence of cover, substrate type, light, moisture, temperature, approaches, directional fencing, human use and anthropogenic noise in the area, species-specific preferences, and time from installation to account for animal learning for finding structures (Foster and Humphrey 1995, Clevenger and

Waltho 2000, Jackson and Griffin 2000, Clevenger et al. 2002, Mata et al. 2005, Huijser et al. 2007). These concerns need to be addressed within the context of project logistics, which include costs of the structure, available material and expertise, physical limitations of the site (e.g., soil, terrain, hydrology); further, it is important to collaborate with transportation and land-use planners well in advance of construction.

Species-specific preferences are important factors in designing effective wildlife crossing structures (Clevenger et al. 2002, Iuell et al. 2003, Hardy et al. 2007). Our recommendations incorporate findings from other projects in considering location, design, and construction of crossing structures. Data and specifications on suitable size, design, planning, siting, construction, and use of crossing structures for several ungulates are well documented (e.g., Dodd et al. 2007, Dodd and Gagnon 2010). We recommend adopting design specifications for ungulates in transportation corridor projects in the NRU to reduce road-related mortality and increase connectivity for jaguar prey. However, data on the efficacy of various crossing structures are limited for carnivores generally and jaguars specifically. Thus, we offer recommendations for planning, designing, siting, and constructing crossing structures for jaguars based on data on similar-sized carnivores, particularly puma, assuming pumas and jaguars respond to roads and wildlife crossings similarly.

In general, road crossing structures for jaguars should be large overpasses and underpasses placed correctly on the landscape with associated fencing to guide jaguars to the structures and jump-outs (earthen ramps that provide opportunities to move outside of the fenced section of roadway if animals do access the road surface and become trapped between fences). We do not recommend multi-use structures, designed for use by both wildlife and humans, for the crossing of jaguars. In areas where it would be impractical to exclude human use, steps should be taken to exclude vehicles, minimize damage to vegetation, educate humans, and strongly discourage human use at night when jaguars and ungulates are most active (Paul Beier, Northern Arizona University, personal communication). Clevenger and Huijser (2011) offered these recommendations for pumas based on a synthesis of 10 years of monitoring and research of crossing structures in North America. More specifically, pumas in Banff National Park used a variety of crossing structures, including overpasses, open-span underpasses, 7 m wide by 4 m high oval culverts, and 2.5 m wide by 3 m high box culverts (Clevenger et al. 2002, Forman et al. 2003).

Crossing structures intended for jaguars should be located far from human activity with sufficient cover leading to the passage. Gloyne and Clevenger (2001) and Clevenger et al. (2002) concluded pumas in Banff National Park selected underpasses with these characteristics. Crossing structures intended for carnivores should be built to provide an unobstructed view of the habitat on the far side of the structure (Beier 1995, Foster and Humphrey 1995, Forman et al. 2003, Ruediger 2007). Efforts should also be made to limit artificial light and keep anthropogenic structures from being placed near crossing structures. Beier (1995), Jackson

(1999), and Cramer and Bissonette (2005) found artificial light might discourage pumas from using crossing structures.

Overpasses

Wildlife overpasses include all passages that cross roadways above the level of the traffic and are typically human-made, landscaped bridges or where the road tunnels under terrain (Forman et al. 2003, Iuell et al. 2003, Huijser et al. 2007, Clevenger and Ford 2010, Clevenger and Huijser 2011). Bridges designed as wildlife crossing structures are ideally designed to be shorter in span and wider than conventional vehicular bridges designed to accommodate two or four lanes of traffic. Well-designed wildlife overpasses are engineered to support a thick layer of soil and vegetation, referred to as a landscaped surface that emulates surrounding habitat conditions. Overpasses should provide for the movement of a broad spectrum of taxa, from large mammals to invertebrates, provided suitable design features and habitat elements afford appropriate substrate and cover along the span. The most effective wildlife overpasses exclude roads on or near the overpass and limit other human activities, as they can hinder wildlife use of the structure (Clevenger and Ford 2010). Human use of wildlife overpasses should be excluded or regulated to a narrow pedestrian path, that is closed at night, and signed to direct people to stay on the path and not to picnic, camp, or linger within 400 m of the overpass (Paul Beier, Northern Arizona University, personal communication). Overpasses can be a costly but effective means of minimizing, at least locally, the fragmentation effects of transportation infrastructure for terrestrial taxa (Iuell et al. 2003) when placed, designed, and managed appropriately in combination with fencing that guides wildlife to the crossings while restricting wildlife access to roadway surface crossings.

Wildlife overpasses for jaguars should be like those designed for other large mammals (Iuell et al. 2003, Clevenger and Ford 2010), which are often 50 to 70 m wide, recognizing some current structures are as narrow as 20 to 50 m and others as wide as 100 m or more depending on project logistics. Most European overpass designs are 90 m wide at the ends, narrowing to 70 m at the middle of the span (Jackson and Griffin 2000, Clevenger et al. 2002). We echo the recommendations of Iuell et al. (2003) and Clevenger and Huijser (2011) that the wider an overpass, the more taxa and ecological functions an overpass will encompass. Additionally, overpass width should increase with the length of the structure. Iuell et al. (2003) suggest a minimum width to length ratio greater than 0.8. Related to features that affect an animal's line-of-sight, the arc of an overpass affects an animal's ability to scan for predators as they ascend toward the apex of an overpass; it has been suggested that animals may be more willing to cross flat overpasses and/or overpasses designed with larger arcs because they may perceive predation risk to be lower if they can see more terrain while moving across the overpass (Clevenger et al. 2002, Donaldson 2005).

Vegetation along the span of a wildlife overpass should be designed to guide and provide cover for jaguars across the overpass and ideally should mimic the surrounding local vegetation in order to provide a suitable habitat corridor (Iuell et al. 2003). Maintenance, engineering limitations (e.g., cumulative weight loads), and traffic safety (e.g., preventing trees from falling off an overpass onto passing traffic) are important considerations in selecting suitable plant species native to the local area. Iuell et al. (2003) suggest soil depths of 0.3 m for grasses and herbs, 0.6 m for bushes and shrubs, and 1.5 m for trees. Additionally, overpasses may be rimmed along their edges with an earthen berm that reduces light and noise of the traffic passing under the structure, which may be preferred by some wildlife species (Clevenger and Huijser 2011). An evaluation of wildlife tolerances for light and noise at crossing structures requires further investigation. Interestingly, some species such as elk (*Cervus elaphus*) opt to travel across the overpass on the top of these berms, presumably to increase their line of sight to scan for predators. Generally, overpasses can be quieter than underpasses, provide habitat more similar to the surrounding landscape, and accommodate more species than underpasses (Jackson and Griffin 2000, Iuell et al. 2003).

Underpasses

Wildlife underpasses include passages built as a connection under the level of the traffic, ranging from open-span bridges to small-diameter culverts (Iuell et al. 2003, Huijser et al. 2007, Clevenger and Ford 2010, Clevenger and Huijser 2011). While typically designed for vehicle passage over wetlands or deep canyons (i.e., not built specifically for wildlife movement), span bridges, viaducts, and causeways across these natural features can provide ideal passageways for jaguars and their prey, particularly for animals that may preferentially travel along water or riparian features that the road spans. In situations where a roadway crosses a valley or other area that lies lower than the target level of the infrastructure, a low viaduct is an ecologically-preferred alternative to adding fill with culverts to accommodate water passage under an embankment where a road passes over the topographic chasm (Iuell et al. 2003). Viaducts and similar structures provide better habitat linkages and are suitable for a wider range of species than other types of underpasses (Iuell et al. 2003).

Gloyne and Clevenger (2001) monitored 22 crossing structures along 45 km of the Trans-Canada highway in Banff National Park year-round for wildlife passage during 1996-2000. They found pumas tended to use open-span underpasses more than other crossing structure types. This finding was further supported by a comparison of overpasses with neighboring underpasses located within 2 km (and therefore potentially available to the same individual pumas), confirming that underpasses received greater use. They also found a significant positive correlation between passages made by pumas through all types of wildlife crossing structures considered (including bridge, metal culvert, and concrete-box culvert underpasses) and those made by mule deer (*Odocoileus hemionus*) and white-tailed deer (*O. vigrinianus*). Gloyne and Clevenger (2001) also found pumas used all wildlife crossing structures (including underpasses) more than expected in the winter months and less than expected during the summer. The authors suggested this seasonal pattern was a function of seasonal elevation changes made by pumas in the Bow Valley and observed elsewhere (e.g., Logan and Irwin 1985, Jalkotzy and Ross 1993).

The wildlife crossing structures (including underpasses) that received the highest number of puma passages in Banff were those situated close to high quality puma habitat. Assuming some similarities in behavioral responses to roads and wildlife crossings between pumas in Banff and jaguars in the NRU, Gloyne and Clevenger's (2001) results provide quantitatively-supported insights to design considerations for jaguars.

In situations where the roadway is built on hilly terrain, or an embankment where fill is used to maintain roadway elevation over undulating topography, underpasses may be constructed for wildlife passage. Although underpasses are cited as less suitable for connecting habitats due to the lack of light and water allowing only limited growth of vegetation (Iuell et al. 2003), well-designed underpasses do provide safe passage opportunities for wildlife; depending on the species behavioral tendencies and perceptions of risk, underpasses may be preferentially used if the limited cover of an overpass leaves animals exposed and vulnerable to predation.

The dimensions of wildlife underpasses are measured by their height, width, and length. The length of an underpass generally corresponds to the width of the roadway plus the additional distance that the base of the fill under the roadway requires (depending on the topography and engineering design approach); however, the width and, to a lesser degree, the height, can be designed according to species-specific requirements (Iuell et al. 2003). Ideally, wildlife underpasses should not be greater than 70 to 80 m in length except in special situations, such as spanning greater than six-lane highways or spanning highways in addition to other types of infrastructure (for example, frontage roads and railway line; Clevenger and Huijser 2011). Clevenger and Huijser (2011) recommend the use of underpass measures (length, width, height) in conjunction with other structural (e.g., divided vs. undivided highway configurations) and environmental (e.g., habitat quality, target species) factors when designing wildlife underpasses. General recommendations for minimum wildlife underpass dimensions vary and are species-specific. General recommendations for the crossing of multiple species are underpasses at least 7 m, preferably >12 m, in width and at least 4 m in height (Iuell et al. 2003, Clevenger and Huijser 2011). These general specifications are primarily driven by ungulate use patterns and would also allow for the passage of large carnivores that will use smaller structures (e.g., Beier 1995, Clevenger and Huijser 2011).

The dimensions of an underpass are often indexed or standardized as relative openness (also called its "openness ratio") and measured as the product of the opening width and opening height divided by the length of the crossing (width x height / length) (Reed and Ward 1985, Gordon and Anderson 2003, Iuell et al. 2003, Servheen and Lawrence 2003). For example, an underpass with a width of 12 m, a height of 4 m, and a length of 25 m would have a relative openness index of 1.9. We, following Clevenger and Huijser (2011), however, do not recommend the use of the openness index in planning and designing wildlife crossing structures because the relationship between openness and underpass use may be species-specific and time dependent, variations in how openness is measured can occur (e.g., as an index, a ratio, or simply a state or concept), and designing for the "minimum" is not recommended or appropriate in most cases.

In many landscapes, long-distance movements by carnivores are often associated with water or riparian habitats (Noss 1991, Hilty et al. 2006), and this is particularly true for more xeric regions such as the northern extent of the NRU (e.g., Atwood et al. 2011). Thus, for jaguars in many parts of their range, higher probability crossing locations are likely to be associated with water and therefore may already have bridges spanning and near the riparian areas. Additionally, because of the associated water at these potential high probability crossing locations, any underpass constructed or modified for wildlife would likely also serve the dual-purpose of maintaining and managing water flow.

Dual-purpose underpass structures are designed to accommodate dual needs of moving water and wildlife (Clevenger and Ford 2010:40, Clevenger and Huijser 2011:139). They are generally located in multi-species wildlife movement corridors given their association with riparian habitats. These underpass structures have been shown to accommodate movements of several large mammal species, and use will depend on how the structure may be adapted for each species' specific crossing requirements. According to Clevenger and Ford (2010), for these types of underpass structures, it is important to include travel paths adjacent to the water that are generally at least 3 m wide and have a vertical clearance of 4 m. Placement of these travel paths will be important such that they are available even during periods of high-water flows. However, some smaller structures may have travel paths at least 2 m wide with 3 m vertical clearance (see Clevenger and Ford 2010). For example, Beier (1995) observed dispersing pumas in coastal southern California regularly crossed under highway bridges built to accommodate watercourses. Dispersers and adults observed in that study, however, usually avoided large and small culverts under freeways or two-lane rural highways in the absence of fencing to direct animals away from the road and toward culverts. Wildlife fencing would have likely increased puma use of culverts (Paul Beier, Northern Arizona University, personal communication). One male puma, however, made frequent use of 1.8 m box culverts to cross under an eight-lane freeway.

Fencing

Fencing alone is an effective means of reducing wildlife-vehicle collisions; however, without crossing structures to accommodate wildlife movements under or over roadways, this approach increases habitat fragmentation and decreases landscape permeability. Thus, fences are considered a mitigation measure for fragmentation and habitat connectivity only in combination with wildlife crossing structures that effectively compensate for the negative barrier effects of fences by accommodating wildlife movements (Iuell et al. 2003, Jaeger and Fahrig 2004, Clevenger and Huijser 2011). The efficacy of overpasses and underpasses reducing wildlife-vehicle collisions and enhancing connectivity is highly dependent on associated wildlife fencing that keeps animals off roadways and funnels them towards crossing structures (Clevenger et al. 2002, Iuell et al. 2003).

Exclusion fencing needs to be designed to funnel jaguars and their prey toward crossing structures while preventing them from jumping or climbing over, crawling or digging under, or pushing through to the roadway. Clevenger and Huijser (2011) suggest fencing configuration used to mitigate road impacts depends on several variables associated with the specific location, primary adjacent land use, traffic volumes, and the potential need to accommodate intersecting access roads. Both sides of the road must be fenced and fence ends across the road need to be symmetric and not offset or staggered. Continuous fencing is most often associated with large tracts of public land with little or no interspersed private property or in-holdings. Long stretches of continuous fence with fewer gaps reduces problems of managing wildlife movement around multiple fence ends and where other roads or driveways access the fenced roadway. Partial or discontinuous fencing is more common with highway mitigation for wildlife in mixed (public and private) land use areas. This fencing strategy generally receives wider acceptance by public stakeholders, but requires additional measures such as modified cattle guard designs at fence openings (e.g., where driveways or other roads access the stretch of road that is fenced to prevent wildlife access) to be installed and monitored to discourage wildlife movement through fence gaps and onto the roadway (see Clevenger and Huijser 2011:170-173).

Fence material should be woven-wire (page-wire) or galvanized chain-link fencing. Clevenger and Huijser (2011:173-174) present a suite of fencing and fence post design specifications. Fence material must be attached to the back-side (non-highway side) of the posts, so impacts from vehicles that may leave the road only take down the fence material and not the fence posts; this also reduces the severity of damage and injury to vehicles and drivers because the fence can give way more easily. Fences 2.2 to 2.4 m tall prevent deer from jumping over (Ward 1982, Iuell et al. 2003, D'Angelo et al. 2005, Clevenger and Huijser 2011). Smaller fence mesh; metal, as opposed to wooden, posts; and outriggers (90 degree lips installed at the top of fencing) help prevent bears (*Ursus* spp.) and pumas from climbing over fences (Clevenger et al. 2001, Hardy et al. 2007, Clevenger and Huijser 2011). Burying the bottom of the fence or a section of chain-link fence spliced to the bottom of the fence approximately 1 m, often referred to as a buried apron or skirt, can limit animals from crawling or digging under fencing (Woods 1990, Clevenger et al. 2001, Clevenger and Huijser 2011).

Despite the best fencing designs, wildlife will occasionally gain access and become trapped inside fenced roadways creating a hazardous situation for drivers and wildlife alike (D'Angelo et al. 2005). Animals able to climb fencing (e.g., bears, pumas, jaguars) will likely exit fenced roadways the same way (Hardy et al. 2007). Jaguar prey, primarily ungulates, however, require features designed to allow for safe exit from the roadway. One-way gates allow animals to exit; however, the reluctance of some species to use gates, some species learning to use gates to access the roadway, and lack of proper maintenance or people available to respond and open these gates when ungulates are trapped inside the fences limit their effectiveness (Woods 1990, Hardy et al. 2007). Alternatively, jump-out ramps are earthen, sloped surfaces that lead from the roadway to the top of the fence, allowing animals, particularly ungulates, caught inside the roadway to escape and preventing animals from using jump-outs to "jump in" to access the roadway. The most effective ramps are placed at V-shaped funnels in the fencing and vegetated similarly to the natural surrounds (Waters 1988, Bissonette and Hammer 2000). Small sections of perpendicular fencing on the jump-outs can also intercept and guide animals to jump out as they move along the inside of the fence. A consideration requiring further research is that jump-outs could enable jaguar access to the roadway.

Wildlife often access fenced roadways with greatest frequency at the ends of fencing (Ward 1982, Waters 1988, Woods 1990, Foster and Humphrey 1995, Clevenger et al. 2001). Clevenger and Huijser (2011) suggest fence ends should terminate at a wildlife crossing structure. If a wildlife crossing cannot be installed at the fence ends, then fences should terminate in the least suitable location or habitat for wildlife movement—i.e., places wildlife are least likely to cross roads, such as a cliff (Clevenger and Huijser 2011). Additionally, fences should end in areas with high motorist visibility, reduced vehicle speeds, and proper signage to alert drivers of potential wildlife activity. Measures designed to limit roadway access at fence ends include wing fencing, cattle or wildlife guards, electric fences, and stone cobble that hinders hooved animals' mobility (Clevenger et al. 2001, Hardy et al. 2007, Clevenger and Huijser 2011:170-173).

Fences are not permanent structures and are subject to damage from and being compromised by vehicular accidents, falling trees, soil erosion, excavation by animals, flooding, and vandalism (Clevenger and Huijser 2011). We suggest checking fences at least every 6 months by walking the entire fence line to identify and repair gaps, breaks, and other defects that compromise the utility of the fence in preventing wildlife access to the roadway. Thus, the costs of monitoring and repairing fences should be budgeted as a recurring annual expense.

Finally, fencing may be difficult for some animals to see and thus they may literally run into the fences, with the potential of creating a prey trap for panicked animals repeatedly hitting the fence while trying to flee from a threat, particularly if the animals are encountering the fence for the first time (Anthony Clevenger, Western Transportation Institute, personal communication). It may be necessary to weave material though the fence to increase its visibility in areas where this may be happening.

Distance Between Structures

The spacing of wildlife crossings on a given section of roadway will depend largely on the variability of landscape, terrain, population densities, the juxtaposition of wildlife habitat that intersects the roadway and the mobility and dispersal characteristics that contribute to connectivity requirements for different species (Clevenger and Huijser 2011). In landscapes that are highly fragmented with little natural habitat bisected by roadways, there are generally fewer appropriate opportunities to incorporate wildlife crossings compared to relatively intact, less fragmented landscapes. Distances between structures will depend on habitat features providing movement corridors for jaguars and their prey, adjacent land use planning and management activities that affect tracts of suitable habitat adjacent and leading to crossings, and the availability of connectivity linkages to a larger network of movement corridors (Clevenger and

Huijser 2011). Clevenger and Huijser (2011) summarized several large-scale existing and proposed mitigation projects in North America, finding wildlife crossing structures are variably spaced but average about 1.9 km apart (range 1.5 – 6.0 km).

The specific siting of wildlife crossing structures is equally as important as their design (Clevenger and Huijser 2011). Projects that have inserted crossing structures at regular intervals have been attempted (e.g., Phase 1 of the Banff Wildlife Crossings) but this approach has been deemed suboptimal compared to placing structures at variable distances apart taking the context of habitat, landscape, land use, and wildlife movement corridors into account. There are a number of methods, including least-cost path, resource-selection functions, circuit and graph theory, and Brownian bridges, used to determine key locations where important wildlife habitat and transportation infrastructure intersect (Matthews et al. 2014). These methods enable ecologists, engineers, and transportation specialists to construct appropriate wildlife crossing structures at optimal locations along transportation corridors.

Monitoring and Evaluation

Monitoring wildlife movements pre- and post-construction is a key element in selecting optimal crossing structure locations and evaluating their success. Monitoring can range from a simple, jaguar-specific evaluation within the highway corridor to more complex ecological processes and functions within regional landscapes of conservation importance. Pre-construction monitoring can offer important data and insights for justifying the specific location for a crossing structure; simultaneously, or in conjunction, preconstruction monitoring can establish baseline conditions from which changes post-construction can then be assessed to determine the effectiveness of the measures. Changes in animal-vehicle collision rates and wildlife crossing rates are commonly assessed, but there are numerous other ecological processes that may also be measured before and after mitigation is installed to determine the effect of these investments. Ideally, monitoring and research questions should address wildlife-vehicle collisions and ecological processes together (Hardy et al. 2007). Clevenger and Huijser (2011:67) presented 5 biological functions encompassing 3 levels of biological organization (genes, species/population, community/ecosystem) wildlife crossing structures should provide:

1) Reduced mortality and increased movement (genetic interchange) within populations;

2) Meeting biological requirements such as finding food, cover and mates;

3) Dispersal from maternal or natal ranges and recolonization after long absences;

4) Redistribution of populations in response to environmental changes and natural disturbances (e.g., fire, drought); movement or migration during stressful years of low reproduction or survival; and

5) Long term maintenance of metapopulations, community stability, and ecosystem processes.

These functions increase in complexity, cost, and time required to properly monitor effectiveness. Following from these functions, Clevenger and Huijser (2011:70–71) outlined a framework that can be used to formulate management questions, select methodologies, and design studies to measure performance of wildlife crossing structures in mitigating road impacts. Generally, the framework includes:

1) Establishing goals and objectives;
2) Establishing baseline conditions;
3) Identifying specific management questions to be answered by monitoring;
4) Selecting indicators;
5) Identifying control and treatment areas;
6) Designing and implementing a monitoring plan; and
7) Validating relationships between indicators and benchmarks.

With goals and objectives defined, the parameters of interest will drive the selection of methods to obtain relevant data. There are a variety of survey methods available to monitor wildlife and the performance of wildlife crossing structures. Methods range from the relatively simple (e.g., reporting of wildlife-vehicle collisions by transportation agency personnel) to the complex (e.g., capture and global positioning system [GPS] tracking of individual animals). Clevenger and Huijser (2011:Appendix E) described many methods that can be used to meet a number of monitoring objectives, including considerations on focal species, season, cost scenarios, and location.

If specific thresholds of change in parameters of interest are used in defining success or effectiveness (e.g., crossing structures will be considered "effective" if animal-vehicle collisions are reduced by 50%), statistical power analyses should applied to ensure that such a change can be detected (e.g., Hardy et al. 2006:60, Craighead et al. 2011:6). Very small thresholds of change may not be detectable given the inherent variability of the data and sampling effort. Preconstruction data collection can be used to provide an estimate of variability that is necessary for power analysis; these analyses can also determine the appropriate sampling effort (intensity and duration of sampling) that may be necessary for detecting the level of change (or, vice versa, power analysis may be applied to determine what thresholds can be detected and therefore what definitions of success may be realistic for managers to expect or anticipate).

Wildlife-Vehicle Collision Data

The collection of data on wildlife-vehicle collision data by transportation agency and law enforcement personnel is a common monitoring methodology (Clevenger et al. 2002, Knapp et al. 2004, Hardy et al. 2007, Clevenger and Huijser 2011). These data can be applied to calculating rates of wildlife-vehicle collisions pre- and post-construction and evaluating the effectiveness of wildlife fencing. Jaguar-vehicle collision rates in the NRU are likely such a rare event, these data will have limited species-specific application. However, these data could be of value in reducing collision rates and addressing ecological processes for jaguar prey species. Data on road-killed wildlife are often collected during regular work conducted by highway crews, can be tailored to multiple species, and come at relatively low cost. However, this method of monitoring requires both spatially and temporally consistent survey efforts by crews for data to be valid and useful for analysis. Hardy et al. (2007) offer the following considerations when requesting, compiling, analyzing, and applying results from wildlife-vehicle collision databases:

1) Sampling framework: who collected the data and how were the data collected;

2) Sampling intent: what was the intent for collecting wildlife-vehicle collision data;

3) Sampling effort: were wildlife-vehicle collisions reported via systematic monitoring methods or opportunistic observations;

4) Sources of error: to what degree has under-reporting, spatial inaccuracies, and observer bias or fatigue affected the dataset;

5) Other parameters: what other ancillary information was recorded with each wildlife-vehicle collision report; and

6) Combining wildlife-vehicle collision datasets: how might differences in sampling areas, time periods, or methods affect the combined dataset and is it possible to detect and reduce duplicate observations.

Wildlife-vehicle collisions are often documented incidentally or opportunistically, resulting in a dataset that underrepresents and inconsistently reports collisions. Systematic survey approaches can reduce, but not necessarily eliminate, underrepresentation in opportunistically collected data. Even consistent and routine monitoring may underestimate collisions by 12-16 times or more for some species (Slater 2002). Sources of process error and sampling variation will also affect collision and road-kill datasets (Hardy et al. 2007). Sources of process error include disappearance of carcasses (e.g., carcasses may be scavenged or removed from roadway before research documents the road-kill) and animals may die away from the roadway where road kills may not be detected (Slater 2002, Sielecki 2004). Sources of sampling error include non-response error, observer fatigue or observer bias, errors in reporting, and poor training (Clevenger et al. 2002). Spatial accuracy of reported road-killed wildlife is also necessary for effective mitigation and monitoring (Clevenger et al. 2002). Clevenger and Huijser (2011) estimated low associated costs, consisting of training transportation agency maintenance crews and routine refresher training and meeting with crews to encourage data collection.

These considerations limit the use of wildlife-vehicle collision data to varying extents. However, careful assessment, screening, analysis, and interpretation of results using such data can provide an indication of areas of concern for wildlife-vehicle collisions for more specific study to assess how mitigation measures might affect collision rates.

Tracking Beds

Mammal tracks can be used to document presence and movements relative to roads and mitigation measures, and potentially, population trends (Clevenger and Waltho 2000, Clevenger et al. 2002, Ng et al. 2004, Long et al. 2008). Track beds are constructed from numerous media (e.g., existing substrates, sand, a mixture of sand and silt, or marble dust) deposited in a linear bed (typically about 2 m in width) across culvert entrances or within the culvert itself (Scheick and Jones 1999, Singleton and Lehmkuhl 1999, van Manen et al. 2001, Ng et al. 2004, Mata et al. 2005, Hardy et al. 2007, Clevenger and Huijser 2011). Track beds inside culverts and crossing structures protect tracking media and tracks from wind and rain, providing fairly reliable data when check and raked smooth every 3-4 days (Clevenger and Waltho 2000, Clevenger and Huijser 2011). Depending on availability of tracking media, this technique is low cost and low tech, although reading and interpreting tracks requires trained personnel. Clevenger and Huijser (2011) estimated personnel costs of $1,300 for one month of monitoring at 10 days of work per month at $130/day ($16/hour) and low equipment costs (rake, personal data assistant, digital camera, tape measure, field guide to animal tracks).

Camera and Video Monitoring

Motion and heat-activated remotely-triggered cameras record images of wildlife, providing occurrence data (Long et al. 2008). Cameras can be set up to capture images of animals near or using a crossing structure, moving along a trail, or over larger areas monitored in a sampling array. Cameras allow for generally unambiguous species identification, low labor costs, deployment during all seasons and locations, a permanent record, and photographs for public outreach. An advantage of cameras over tracking is individual jaguars can be identified, allowing for more detailed analyses (Maffei et al. 2011, Polisar et al. 2014). Video monitoring provides additional insights into animal behavior, including failed crossing attempts and speed of crossing. Disadvantages include high initial costs and the risk of theft. Clevenger and Huijser (2011) estimated high initial costs ($550-800 per camera, including protective, theft-resistant box, data cards, and batteries). Labor costs are low for surveys at particular crossing structures, but increase as larger arrays are sampled.

Radio-Tracking Wildlife Movements

Radio telemetry (very high frequency [VHF] or global positioning system [GPS]) studies can provide comparative data on wildlife movements relative to roads, wildlife fencing, and crossing structures (Chruszcz et al. 2003). Individual jaguars can be followed for years before and after construction (Dodd et al. 2003). These technologies can also provide insights on behavior, mortalities, and demographic parameters of a population if sample sizes are large. Radio telemetry provides direct confirmation that animals have successfully crossed the roadway. However, depending on the temporal sampling interval, it is often difficult to confirm whether radioed individuals are crossing at grade on the roadway or utilizing crossing structures. Some GPS technologies with short durations between collected locations are coming closer to addressing this issue. Cost of radio-telemetry methods, including logistics coordination, the purchase of equipment, and capture and marking of animals, is high compared to other methods.

Monitoring and Evaluation Summary

The ideal evaluation of crossing structure performance involves the collection of data before and after the installation of the mitigation (Hardy et al. 2007). Pre-mitigation data collection should begin as soon as possible to maximize preconstruction sampling and minimize the noise of environmental and demographic stochasticity. Small sampling windows ≤ 2 years may lead to biased results, misleading managers to shortsighted conclusions (Clevenger et al. 2002). Similarly, immediately conducting post-construction monitoring may yield biased results because animals often need time to learn to navigate fencing and use crossing structures (Clevenger et al. 2002). Understanding the long-term and landscape-scale effect of wildlife crossing structures in terms of communities, biodiversity, ecosystem processes, and landscape ecology may take ≥ 10 years before suggesting results (Clevenger et al. 2002, Hardy et al. 2007), especially for long-lived, slow-reproducing species that occur in low population densities, such as jaguars in the NRU.

Cost Scenarios

The installation of wildlife crossing structures to mitigate the effects of roads for wildlife conservation and public safety is most economical during road expansion or upgrade projects (Clevenger and Huijser 2011). Thus, funding for road mitigation measures such as wildlife crossing structures is most likely to originate from specific transportation projects that address multiple transportation management concerns, one of which may reduce vehicle collisions with wildlife and provide safe wildlife passage across roadways. This project-level approach should be nested within a systems-level analysis of transportation management concerns and priorities over a much larger area than specific road projects (Clevenger and Huijser 2011, Matthews et al. 2014). Partners in a systems-level analysis for the NRU would include the U.S. Federal Highway Administration, Mexican Secretariat of Communication and Transportation, and federal and state transportation, natural resources, and regional planning agencies along with various local communities in the U.S. and Mexico. Rather than seeking to place a specific crossing structure at the scale of a particular project, the systems perspective identifies stretches of highway requiring mitigation at the transportation-system or landscape scale and helps to identify the appropriate type of mitigation given the system-wide goals and available resources.

Information about wildlife crossing structures throughout the entire NRU is lacking. Specifically, we were unable to find examples of wildlife crossing structures designed and built in Mexico; therefore, we are unable to develop cost scenarios for different types of structures and projects in Mexico. However, in Arizona, biologists, engineers, planners, and land managers from 9 public agencies have identified large blocks of protected wildlife habitat, potential wildlife movement corridors through and between them, factors that could possibly disrupt these linkages zones, and opportunities for conservation (The Arizona Wildlife Linkages Workgroup 2006). The Arizona Wildlife Linkage Assessment is an initial effort to identify potential linkage zones that are important to Arizona's wildlife and natural ecosystems. This nonbinding assessment serves as an informational resource to planners and engineers, providing suggestions for the incorporation of measures to protect these linkage zones into their management planning to address wildlife connectivity as well as driver safety at an early stage of the process.

Two current projects in southern Arizona, Arizona State Route (SR) 77 along the Santa Catalina – Tortolita Linkage and Arizona SR 86 along the Kitt Peak Linkage, offer examples of effective system- and project-level planning with current cost estimates for the design and construction of wildlife crossing structures.

Arizona State Route 77: Santa Catalina – Tortolita Linkage

The Arizona Department of Transportation (ADOT) and Arizona Game and Fish Department are working collaboratively to increase the permeability of SR 77 for wildlife and to maintain habitat connectivity by installing wildlife crossing structures as part of the SR 77 Pinal County Line to Tangerine Road Widening Project (Arizona Department of Transportation 2009). SR 77 traverses much of the length of Arizona, stretching from its northern terminus at the boundary of the Navajo Nation north of Holbrook to its junction with Interstate 10 in Tucson. The highway bisects the area between the Santa Catalina Mountains and the Tortolita Mountains, recognized as the Santa Catalina – Tortolita Linkage, an area critical to wildlife movement (The Arizona Wildlife Linkages Workgroup 2006). Project improvements include widening SR 77 from 4 to 6 traffic lanes and increasing traffic lane and shoulder widths. Design considerations for the wildlife crossing structures were based on the structures constructed in Banff National Park across the Trans-Canada Highway (Ford et al. 2010, McGuire 2012).

The original project proposal outlined an $8,230,000 budget to install 2 wildlife underpasses, 1 wildlife overpass, wildlife fencing, escape ramps, and associated design and engineering costs (Arizona Department of Transportation 2009:17-19). The first proposed wildlife underpass will be 3.7 m high, 9.8 m wide, and 57.9 m long, with a total installed cost of $615,790 (Arizona

Department of Transportation 2009:10). The second proposed wildlife underpass will be 3.7 m high, 15.2 m wide, and 57.9 m long, with a total installed cost of $729,680 (Arizona Department of Transportation 2009:10-11). The proposed wildlife overpass will be 6.1 m high, 45.7 m wide, and 57.9 m long composed of precast concrete units, with a total installed cost of $2,622,500 (Arizona Department of Transportation 2009:12-13). Landscaping, 9,711 m of wildlife fencing, and 1 escape ramp are estimated to cost $100,000, $950,400, and $50,000, respectively. The project has since been revised to include 2 crossing structures, 1 overpass and 1 underpass linked with wildlife fence and integrated with 3 existing large bridges. Construction for this project was initiated in the summer of 2014 and is anticipated to be completed by spring 2016 (Arizona Department of Transportation 2014).

Arizona State Route 86: Kitt Peak Linkage

ADOT and the Tohono O'odham Nation are working collaboratively to integrate wildlife connectivity needs into the ongoing project planning for segments of SR 86. SR 86 is the highway linking Tucson to the Tohono O'odham Nation and its Tribal seat of government in Sells, Arizona (Tohono O'odham Nation 2011, 2014). The highway continues west, linking to SR 85, Ajo, Mexico, Gila Bend, and Interstate 8. The portion of SR 86 between mile post 130 and 138 is identified as the Kitt Peak Linkage, one of the 28 highest-priority linkages, reflective of its biological value for mule deer, javelina (*Tayassu tajacu*), puma, bighorn sheep (*Ovis canadensis*), and jaguar within a north-south string of sky islands stretching along the Baboquivari Mountain Range west of the Altar Valley from Mexico to Interstate 8 and beyond (Tohono O'odham Nation 2011, 2014). ADOT has embarked on widening the existing narrow 2-lane roadway with limited shoulders to include paved 2.4-m shoulders and 8.1-m vehicle-recovery zones to improve motorist safety (Tohono O'odham Nation 2011, 2014). Vehicle-recovery zones are the total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles.

To address wildlife connectivity along SR 86 within the Kitt Peak Linkage, the Tohono O'odham Nation is collaborating with ADOT and the Pima County Regional Transportation Authority (RTA) to install 4 wildlife crossing structures (2 overpasses and 2 underpasses), wildlife fencing, escape ramps, and cattle guards along the combined 13.8-km Kitt Peak and Santa Rosa widening project limits (Tohono O'odham Nation 2011, 2014). The proposals and planning documents for this project, summarized by structure type below, provide a range of cost scenarios to inform future projects.

The Tohono O'odham Nation (2011:15) considered the design and associated costs of two underpass structure approaches (Table 1). Underpasses with roadway barriers entailed installing 14.6-m long structures with guard rails or walls along the roadway in lieu of 8.1-m vehicle-recovery zones. This area may consist of a shoulder, a recoverable slope, a non-recoverable slope, and/or a clear run-out area. Although providing for a shorter underpass structure and possibly providing passage for a wider range of species, this option also presented the greatest concern for motorist safety associated with the barriers. Thus, the RTA approved the installation of two 26.8-m long precast arch underpasses to accommodate wildlife movement while providing vehicle-recovery zones to improve driver safety. Although superior for motorist safety, longer underpasses may discourage passage of some species.

The Tohono O'odham Nation (2014:17) proposed the construction of 2 wildlife overpasses, estimated to cost \$1,830/m^2 (Table 1) based on a design being used on SR 77. Both overpasses were proposed to be 43.9 m long to accommodate future addition of 2 travel lanes. This yielded an estimated cost for each overpass (12.2 m wide by 43. 9 m long) of approximate \$980,000. In addition to the structure cost, the overpass estimates include retaining walls (139.4 m^2) previously estimated at \$538/m^2, totaling \$75,000, and earth work involving backfilling and grading the overpass, estimated to involve up to 1,529 m^3 of soil moving at \$72/m^3, or a total of \$110,000 for each overpass site. Overpass structure heights will need to be in excess of 6.1 m above the roadway to accommodate potential oversize loads.

An estimate for wildlife fencing of \$29.53/m along 13,216 m of the project area was used, assuming the wildlife fence would be a retrofit application to extend the height of new right-of-way fence, thus reducing cost (Table 1). Along a second segment of the project area (13,843 m) the cost was estimated at \$39.37/m for a total of \$545,000. The total fence cost for the project (27,364 m) was \$808,000. Escape ramps were estimated at \$6,000 per unit. Sixteen escape ramps were required along the length of the wildlife fence at a total cost \$96,000. Lateral access control cattle guards ranged in price from \$22,000 for a 5-unit cattle guard to \$33,000 for a 7-unit cattle guard, with an estimated total cost of \$82,000.

A variety of engineering, design, planning, and compliance costs are associated with the implementation of all elements of any transportation infrastructure construction project (Table 1). Specific to the SR 86 wildlife mitigation components of the larger construction project, geotechnical investigation and testing, critical to the wildlife overpass design, were estimated at \$100,000. Environmental clearances, surveys, and National Environmental Protection Agency (NEPA) compliance was estimated at \$50,000, archaeological survey and recovery \$150,000, right-of-way survey and temporary construction easements \$150,000, and engineering design and development of final plans, cost estimates, and bid materials were estimated at 20% of total construction costs. Contractor mobilization and traffic control were both estimated at 15% of the construction costs, construction contingencies at 25%, and RTA 10% and ADOT 5% construction administration.

Summary

Roads affect wildlife populations and their ability to persist at local and landscape scales. Roads and associated traffic impose direct and indirect impacts to wildlife, including habitat loss and fragmentation, disruption of demographic and genetic connectivity, and road-related mortality. Large mammalian carnivores are particularly vulnerable to these impacts, owing to their large area requirements, low densities, and slow population growth rates. Wildlife crossing structures and associated exclusion fencing, although relatively novel to the North American transportation infrastructure, are maintaining and improving habitat, demographic, and genetic connectivity, and reducing road-related mortality for both people and wildlife. Integrating crossing structures and exclusion fencing into transportation systems through collaborative, interdisciplinary planning, design, placement, construction, and monitoring may prove to be a key element in maintaining and improving connectivity for movement of jaguars, thereby increasing the long-term survival of subpopulations.

Genetic variation among jaguar subpopulations has shown little evidence of significant geographical partitions and barriers to gene flow range-wide. Given this, and the demographic benefits of connectivity, maintaining connectivity between jaguar breeding areas is a vital component in conservation planning for the species. Several models of jaguar corridors among subpopulations throughout their distribution have been developed. Considering existing and proposed improvements of transportation infrastructure throughout the northern distribution of the jaguar and the impacts roadways pose to the persistence and recovery of large carnivores, incorporating wildlife crossing structures throughout the NRU will likely have lasting conservation benefit for the jaguar as well as other wildlife species, in addition to safety benefits for drivers.

Natural resource and transportation agency personnel have used systems-level assessments of wildlife habitat linkages and movement corridors to identify and prioritize segments of transportation networks with high levels of wildlife-road conflict over a large area. Specific placements of wildlife crossings are determined at the project level after a thorough field survey as part of a larger system-level assessment. Species-specific preferences are key considerations in planning, locating, designing, and building wildlife crossing structures and exclusion fencing. Jaguar use of wildlife crossing structures remains unknown, given these structures are largely absent or unstudied within the jaguar's range. Large carnivores exhibit species-specific tendencies in their use of overpasses and underpasses. Given lack of empirical data that would indicate if jaguars have a preference for under- or overpasses, we recommend judicious use of large overpasses and underpasses for the passage of jaguars and their prey, that are well fenced to guide animals to the crossing structures and prevent animals from climbing over or digging under the fencing; have suitable levels of concealment cover; are suitable distances away from development, human activity, and artificial light sources; and are built to provide an unobstructed view of the habitat on the far side of the structure. Monitoring wildlife movements pre- and post-construction is a key element in selecting optimal crossing structure locations and evaluating their success. Ultimately, evaluation and assessment of every wildlife crossing and fencing project yields important insights that can be applied to maximize the return-on-the investment of existing and future projects that are needed to protect wildlife and drivers alike.

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Table 1. Estimated costs for elements of the Kitt Peak Linkage Wildlife Connectivity project along the combined 13.8-km Kitt Peak and Santa Rosa widening project limits on Arizona State Route 86 (Tohono O'odham Nation 2011, 2014).

Project Element	Description	Units	Cost	Total
Construction				
Underpasses with barriers	Precast arch underpass	2.1 m high, 6.1 m wide, 14.6 m long		$313,800
Underpasses with barriers	Precast arch underpass	3.4 m high, 7.3 m wide, 14.6 m long		$337,940
Underpasses with vehicle-recovery zones	Precast arch underpass	2.1 m high, 9.8 m wide, 26.8 m long		$355,540
Underpasses with vehicle-recovery zones	Precast arch underpass	3.4 m high, 9.8 m wide, 26.8 m long		$390,740
Overpasses	Bridge structure	12.2 m wide, 43.9 m long	$1,830/m^2	$979,200
	Retaining walls		$538/m^2	$75,000
	Backfilling/grading		$72/m^2	$110,000
Wildlife fencing	1.8 m fencing	27,364 m	$29.53/m	$808,000
Escape measures	Wildlife escape ramps	16	$6,000 each	$96,000
Access controls	Cattle guard (7 unit)	1 each	$33,000 each	$33,000
	Cattle guard (6 unit)	1 each	$27,000 each	$27,000
	Cattle guard (5 unit)	1 each	$27,000 each	$27,000
Engineering/Design				
Investigation/testing	Geotechnical	1/structure	$50,000	$50,000
Environmental clearing	Surveys and NEPA	1/project	$50,000	$50,000
Right-of-way	Survey and TCE	1/project	$150,000	$150,000
Final design	Final plans, costs	20% of construction cost		
Archaeological	Survey/recovery	1/project	$150,000	$150,000
Mobilization/Administration				
Mobilization		15% of construction cost		
Traffic control		15% of construction cost		
Contingencies		25% of construction cost		
Construction admin		10% of construction cost		
Construction/permit admin		5% of construction cost		

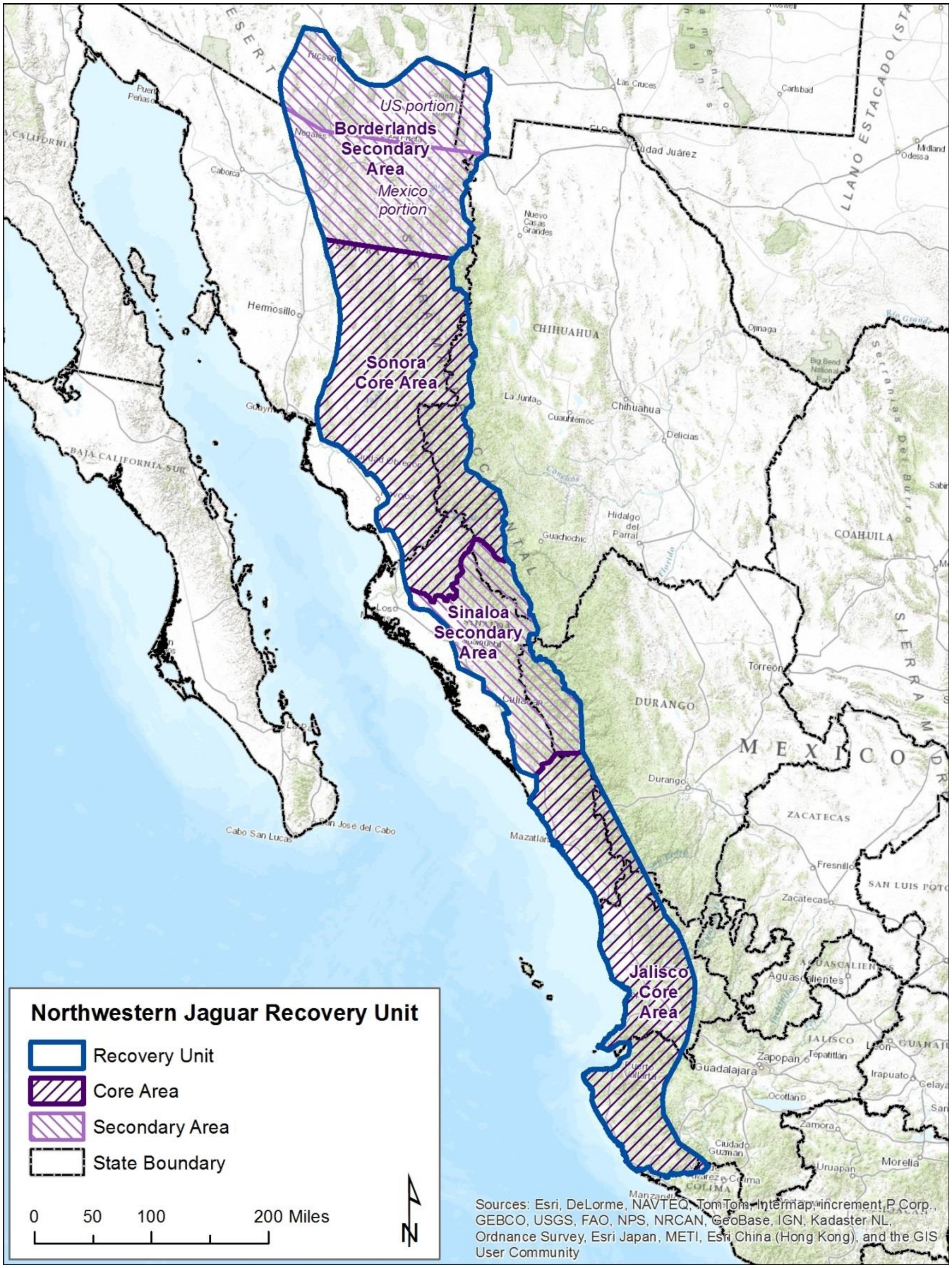

Figure 1. The 226,826 km² Northwestern Jaguar Recovery Unit (NRU) straddles the United States-Mexico border with approximately 29,021 km² in the United States and 197,805 km² in Mexico (Sanderson and Fisher 2013).