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PART 2 - COST EFFECTIVE SOLUTIONS: BEST PRACTICES MANUAL TO REDUCE ANIMAL-VEHICLE COLLISIONS AND PROVIDE HABITAT CONNECTIVITY FOR WILDLIFE

September 2022

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

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16. Abstract

The goal for this manual is to provide practical information for the implementation of mitigation measures that aim to: 1. Improve human safety through reducing collisions with large animals, including large wild mammal species, select free roaming large feral species, and select free roaming large livestock species, and 2. Improve or maintain habitat connectivity for terrestrial wildlife species and selected feral species through safe crossing opportunities. This manual does not include all possible measures that can or may reduce animal-vehicle collisions and maintain or improve habitat connectivity for wildlife. The measures included in this manual are: Barriers (fences) in combination with crossing structures (for large wild mammals and for small wild animal species), roadside animal detection system, Barriers (fences), Barriers (fences) in combination with crossing structures (for free roaming livestock), and culling, relocation, anti-fertility treatment, roadside animal detection systems, barriers (fences), and barriers (fences) in combination with crossing structures (for large feral mammal species such as feral horses and burros).

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Best Practices Manual to Reduce Animal-Vehicle Collisions and Provide Habitat Connectivity for Wildlife

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1263 South Stewart Street

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For the following larger project:

Wildlife Vehicle Collision (WVC) Reduction and Habitat Connectivity

Task 1 – Cost Effective Solutions

Transportation Pooled-Fund Project TPF-5(358)

(Administered by the Nevada Department of Transportation)

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DISCLAIMER

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SUMMARY

The goal for this manual is to provide practical information for the implementation of mitigation measures that aim to:

- Improve human safety through reducing collisions with large animals, including large wild mammal species, select free roaming large feral species, and select free roaming large livestock species.
- Improve or maintain habitat connectivity for terrestrial wildlife species and selected feral species through safe crossing opportunities.

This manual does not include all possible measures that can or may reduce animal-vehicle collisions and maintain or improve habitat connectivity for wildlife. The measures included in this manual are:

A. For large wild mammal species:

- Barriers (fences) in combination with crossing structures

B. For Free Roaming Livestock and feral large mammal species:

Measures for livestock:

- Roadside animal detection system
- Barriers (fences)
- Barriers (fences) in combination with crossing structures

Measures for large feral mammal species:

- Culling
- Relocation
- Anti-fertility treatment
- Roadside animal detection system
- Barriers (fences)
- Barriers (fences) in combination with crossing structures

C. For small animal species:

- Barriers (fences) in combination with crossing structures

1. INTRODUCTION

Implementation of measures aimed at reducing animal-vehicle collisions from a human safety perspective and measures aimed at reducing the negative effects of roads and traffic for wildlife, require knowledge. Knowledge is needed about the types of the effects, the types of effects that one may choose to address, and the locations where action may need to be considered first.

1.1. Types of Effects

While there is much emphasis on mitigating large mammal-vehicle collisions in North America, crashes, dead animals, and associated costs and risks to humans are not the only reason mitigation for wildlife along highways may be considered (Van der Ree et al. 2015). The authors of this report distinguish five different categories of effects of roads and traffic on wildlife (Figure 1):

- Habitat loss: e.g., the paved road surface, heavily altered environment through the roadbed with non-native substrate, and seeded species and mowing in the clear zone.
- Direct wildlife road mortality because of collisions with vehicles.
- Barrier to wildlife movements: e.g., animals do not cross the road as often as they would have crossed natural terrain, and only a portion of the crossing attempts is successful.
- Decrease in habitat quality in a zone adjacent to the road: e.g., noise and light disturbance, air and water pollution, increased access to the areas adjacent to the highways for humans.
- Right-of-way habitat and corridor: Depending on the surrounding landscape, the right-of-way can promote the spread of non-native or invasive species (surrounding landscape largely natural or semi-natural) or it can be a refugium for native species (surrounding landscape heavily impacted by humans).

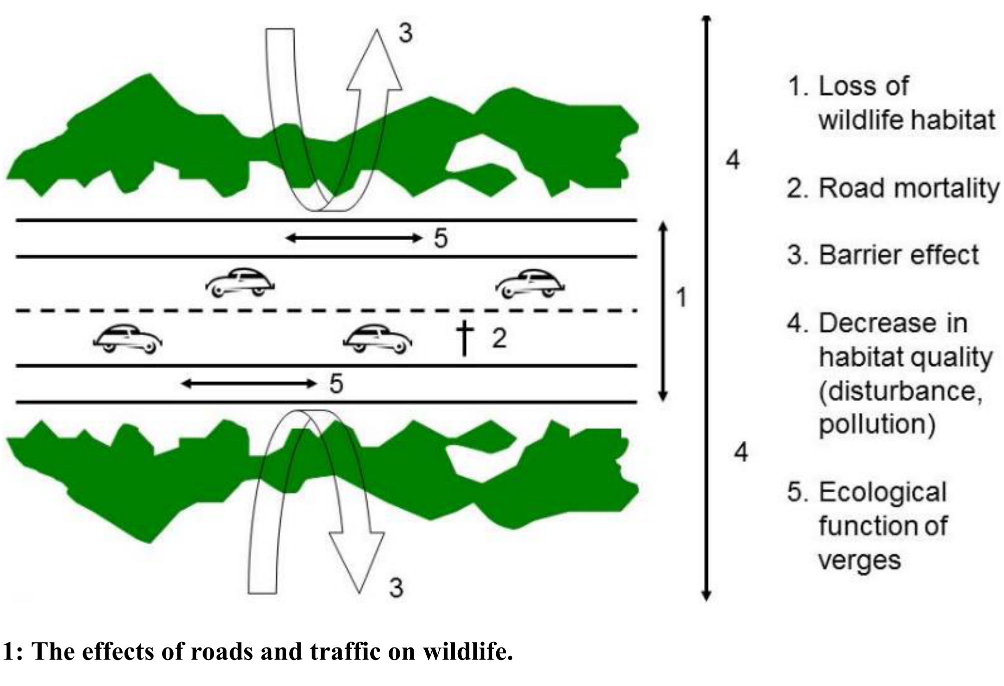

Figure 1: The effects of roads and traffic on wildlife.

1.2. Types of Effects and Associated data

If one chooses to address collisions with large mammals because of a concern for human safety, data are needed on the locations where these types of collisions occur. Along most roads in North America there are two types of large animal-vehicle collision data that can help identify the “worst” road sections:

- **Crash data:** These data are typically collected by law enforcement personnel. For a crash to be entered into the database there is often a threshold (e.g. the minimum estimated vehicle repair cost is at least US $1,000 and/or there are human injuries and human fatalities) (Huijser et al. 2007).
- **Carcass data:** These data are typically collected by road maintenance crews when they remove carcasses of large mammals that are on the road or that are very visible from the road in the right-of-way and that are an immediate safety hazard or a distraction to drivers (Huijser et al. 2007). Note that carcass data are sometimes also collected or recorded by others, e.g. by personnel from natural resource management agencies, researchers, or the general public.

Both types of collision data tend to relate to large mammals only, and they can include both wild species and domesticated species (livestock or feral species). For North America, common large wild ungulates, especially white-tailed deer (*Odocoileus virginianus*), mule deer (*Odocoileus hemionus*), elk (*Cervus canadensis*) and moose (*Alces americanus*) are the most numerous species in the crash and carcass data. Therefore, common large wild ungulates tend to drive the identification and prioritization of road sections where mitigation measures may be considered based on human safety. Medium-sized and small-sized mammals and other species groups such as amphibians, reptiles and birds are usually inconsistently recorded, or not recorded at all, by law enforcement or maintenance personnel (Huijser et al. 2007). Furthermore, crash data typically represent only a fraction (14-50%) of the carcass data, even if both data sets relate to large mammals only (Tardif and Associates Inc. 2003; Riley & Marcoux 2006; Donaldson & Lafon 2008). Finally, the carcass data are far from complete as well; animals that are not very visible from the road in the right-of-way may not be removed and do not get recorded. Wounded animals that make it beyond the right-of-way fence before they die are also usually not recorded at all. Carcass counts underestimate the number of large mammals that are hit, and Lee et al. (2021) calculated a correction factor of 2.8.

If one chooses to reduce direct road mortality of wildlife species, regardless of the possible impacts for human safety, the concern can relate to any species, not just common large mammal species. This means that the species can be large or small, and the species may be common or rare. There may be emphasis on reducing mass mortality (e.g. amphibians or reptiles), e.g. for ethical reasons, regardless of whether a species is endangered or threatened, or whether it has reduced population persistence in an area. There can also be emphasis on reducing direct road mortality, or reducing the probability of direct road mortality, for rare species, including species that have not yet been recorded as road mortality. This may especially apply to species for which direct road mortality is or can be suppressing their population survival probability in an area. Oftentimes, crash data collected by law enforcement personnel and carcass data collected by maintenance personnel are not suited to identify and prioritize the road sections where action should be considered first for small or rare species. Additional data collection may be warranted for small or rare species or species groups in specific areas. One may also conduct spatial analyses based where mitigation measures may be warranted. Such analyses can relate to suitable habitat or potential population viability, regardless of whether the habitat is currently occupied by the concerning species.

One may also choose to reduce the barrier effect of roads and traffic for animals. This is especially relevant for wild species whose movements are not or should not be controlled or limited by people, and for species who would "benefit" from improved connectivity. In general, small and isolated populations have lower population viability than populations that are large and well connected. Reducing the barrier effect of roads and traffic can therefore improve population persistence for a species in an area. It is important to realize that the road sections where the barrier effect may need to be mitigated most urgently, are not necessarily the same road sections where direct road mortality occurs most frequently. In fact, improved connectivity across roads may also be needed where there is no evidence of direct road mortality at all, potentially because the barrier effect is so substantial that animals do not even attempt to cross the road. Nonetheless, reducing the barrier effect on such locations may lead to a larger effective population size because it is better connected thus has a higher population survival probability. Furthermore, improving connectivity across roads may not only be based on the current distribution and movements of animals. It may also be based on conservation efforts that aim to restore habitat and movement corridors across the wider landscape, and on dispersal of individuals that move to far away areas. Dispersing animals may strengthen the viability of small and isolated populations, but they may also colonize or recolonize areas that are not currently occupied by that species. Besides improved population persistence, habitat connectivity across roads may also be required for species that have seasonal migration. This may involve small scale movements (e.g. hundreds of meters for certain amphibian species that move between winter habitat and breeding habitat) or large scale movements (e.g. hundreds of kilometers for certain ungulate species). In some cases, there may be substantial direct road mortality where roads bisect these seasonal migration corridors, but that is not necessarily the case.

One may also choose to address habitat loss, a decrease in habitat quality in a zone adjacent to the road, address the ecological functioning of rights-of-way, especially for non-native invasive species. These concerns all require their own types of data to allow for the identification and prioritization of road sections that mitigation measures may need to be considered for. However, this manual only addresses animal-vehicle collisions (direct road mortality) and the barrier effect of roads and traffic for wildlife species.

In conclusion, if only wildlife-vehicle collision data collected by law enforcement personnel and road maintenance personal are used to identify and prioritize locations along highways that may require mitigation measures, then the concern is typically primarily with human safety and reducing collisions with common large mammal species (wild species, domestic species, or both, depending on the goals and objectives of the project). Road sections that may need to be mitigated for their impact on biological conservation may not be identified or prioritized at all if the "departure point" is human safety. Addressing direct road mortality for small or rare species may require other road mortality data sources, most likely very targeted efforts for specific species in specific areas. This may include road mortality surveys for small animal species at very low speed, e.g. on foot (e.g. Teixeira et al. 2013). Rare species are not only rarely encountered, but the carcasses may be removed (legally or illegally) by others before agency personnel, researchers, or citizen scientists come by. If the interest is to reduce road mortality of rare species, it becomes increasingly likely that reducing roadkill is not only or not primarily about human safety; it becomes more about biological conservation. In this context, it may be a good strategy to not only focus on current road mortality hot spots, but to also address historic roadkill hot spots that may have acted as a population sink in the past and where the population is now so depleted that it no longer shows up as a hot spot for collisions (Teixeira et al. 2017). Therefore, sites that require mitigation for rare species, even if these species have a large body size, may need to be primarily based on suitable habitat or corridors, instead of carcass and crash data, which are inherently rare. Addressing habitat connectivity for wildlife species requires yet other types of data, e.g. population viability analyses, wildlife movement data, and existing or planned habitat and corridors. In some cases, there may be overlap between road sections where direct road mortality occurs and road sections where habitat connectivity is needed most, but this is not necessarily the case. Therefore, it is important to be clear about the “departure point” for the identification and prioritization process for road sections where mitigation measures may be required. If the “departure point” is human safety, the potential “destinations” can be very different compared to the potential “destinations” for a departure point rooted in biological conservation. In other words, depending on the objectives, different road sections may be identified and prioritized for potential mitigation measures (Huijser & Begley 2019).

1.3. Decide on the Approach: Avoidance, Mitigation, or Compensation

While mitigation (reducing the severity of an impact) is common, avoidance is better and should generally be considered first (Cuperus et al. 1999). For example, the negative effects of roads and traffic may be avoided if a road is not constructed, or the most severe negative effects may be avoided by re-routing away from the most sensitive areas (Figure 2). If the effects cannot be avoided, mitigation is a logical second step. Mitigation is typically done in the road-effect zone (Figure 2) and may include measures aimed at reducing wildlife-vehicle collisions and reducing the barrier effect (e.g., through providing for safe wildlife crossing opportunities) (Huijser et al. 2008c; Clevenger & Huijser 2011). However, mitigation may not always be possible, or the mitigation may not be sufficient. In such situations, a third approach may be considered: compensation or off-site mitigation. Compensation may include increasing the size existing habitat patches, creating new habitat patches, or improving the connectivity between the habitat patches that would allow for larger, more connected, and more viable network populations. Finally, in some situations, a combination of avoidance, mitigation, and compensation may be implemented.

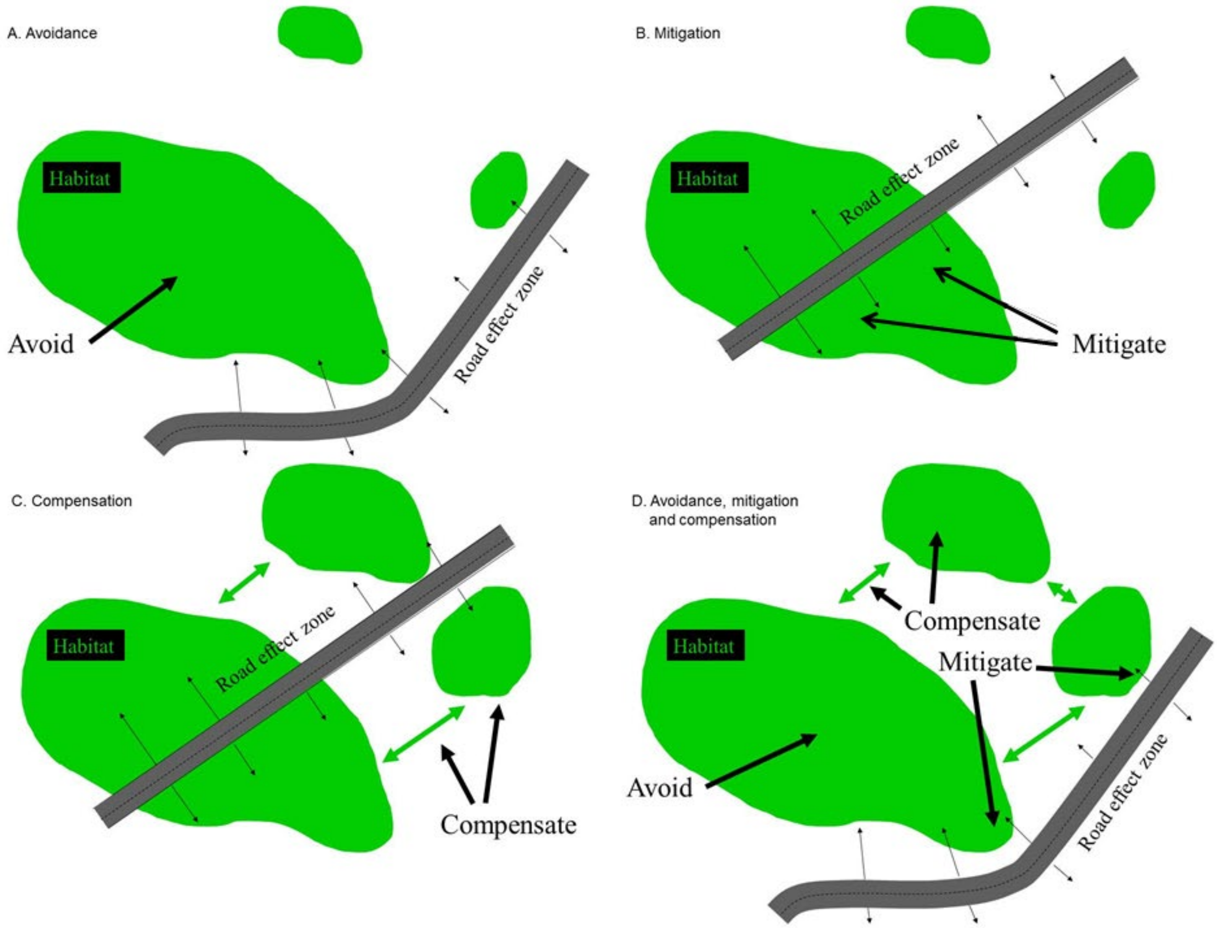

Figure 2: A three step approach: A. Avoidance, B. Mitigation, C. Compensation, D. Combination of avoidance, mitigation and compensation.

2. CONTENT OF THIS MANUAL

2.1. Goals for the Manual

The goal for this manual is to provide practical information for the implementation of mitigation measures that aim to:

- Improve human safety through reducing collisions with large animals, including large wild mammal species, select free roaming large feral species, and select free roaming large livestock species.
- Improve or maintain habitat connectivity for terrestrial wildlife species and selected feral species through safe crossing opportunities.

In this manual, the species groups are defined as:

- “Large wild mammal species”: North American wild mammal species that have a body size and weight larger than a coyote (*Canis latrans*).

- “Feral species”: Horses ((*Equus ferus*), sometimes referred to as “mustangs” or “wild horses”) and donkeys ((*Equus africanus asinus*), sometimes referred to as “wild donkeys” or “burros”) that have escaped from captivity, that have been set free on purpose, or that are descendants from such individuals, and that now live similar to a wild animal species in North America.

- “Free roaming large livestock species”: Cattle and horses that are domesticated, that have owners, and that are kept and raised in an agricultural setting for food, other animal products, or physical labor, but whose movements are not fully restricted and that have access to some highway sections because livestock fences along the right-of-way are either absent or not functional.

- “Terrestrial small wildlife species”: Small wild mammal species (no minimum size for the species, but maximum size is similar to a coyote), wild reptile species, and wild amphibian species in North America that are fully, predominantly or partially terrestrial. This excludes flying species and arboreal species. Note that invertebrates are also excluded.

2.2. Selected Measures

This manual does not include all possible measures that can or may reduce animal-vehicle collisions and maintain or improve habitat connectivity for wildlife. The first filter for the measures included in this manual is that the authors assume that:

- Road and traffic remain (i.e. exclude road removal, and permanent or temporary road closures).
- Culling, relocating and anti-fertility treatment are not acceptable for livestock, but can be considered for feral large mammals.

Additional criteria for the measures included in this manual:

A. Large wild mammal species:

Criteria 1: At least 50% reduction in collisions or direct road mortality (i.e. exclude measures that are less effective, or that lack data on effectiveness).

Criteria 2: Reduce the barrier effect of roads and traffic (i.e. exclude measures that increase the barrier effect of roads and traffic, and exclude measures that do not aim to reduce the barrier effect of roads and traffic).

Based on the literature review (Huijser et al. 2021), this means that the following measure is selected for this manual:

- Barriers (fences) in combination with crossing structures

B. Free Roaming Livestock and feral large mammal species:

Criteria 1: At least 50% reduction in collisions or direct road mortality (i.e. exclude measures that are less effective, or that lack data on effectiveness).

Optional criteria 2a: Assisted connectivity for livestock (see Huijser et al. 2021).

Optional criteria 2b: Non-assisted connectivity for large feral mammals (see Huijser et al. 2021).

Based on the literature review (Huijser et al. 2021), this means that the following measures are selected for this manual:

Measures for livestock:

- Roadside animal detection system
- Barriers (fences)
- Barriers (fences) in combination with crossing structures

Measures for large feral mammal species:

- Culling
- Relocation
- Anti-fertility treatment
- Roadside animal detection system
- Barriers (fences)
- Barriers (fences) in combination with crossing structures

C. Small animal species:

Criteria 1: At least 50% reduction in collisions or direct road mortality (i.e. exclude measures that are less effective, or that lack data on effectiveness).

Criteria 2: Reduce the barrier effect of roads and traffic (i.e. exclude measures that increase the barrier effect of roads and traffic, and exclude measures that do not aim to reduce the barrier effect of roads and traffic).

Based on the literature review (Huijser et al. 2021), this means that the following measure is selected for this manual:

- Barriers (fences) in combination with crossing structures

2.3. Structure of this Manual

This manual has three main sections focused on different species groups:

- Section A: Large wild mammals
- Section B: Livestock and feral large mammals
- Section C: Small animal species

3. GENERAL CONSIDERATIONS

3.1. The Function of the Fences and Crossing Structures

Large mammal fences in combination with wildlife crossing structures are the most robust and effective mitigation measure to both reduce collisions with large and small animal species and maintain or improve connectivity for wildlife. However, it is important to be aware of the different functions of fences vs. the function of crossing structures and how that relates to the "departure point" of a mitigation project.

If human safety and direct road mortality of a species are the primary concern, then:

- Road sections with a high concentration of collisions and dead animals are identified and prioritized (e.g. Panowicz et al. 2020). The target species may be large common mammals if human safety is the primary concern (e.g. Huijser et al. 2008a). If reducing unnatural mortality for rare species is the concern, the target species can be of any body size (e.g. Kramer-Schadt et al. 2004; Huijser et al. 2008a; Boyle 2021).
- From a human safety perspective, it is logical to identify and prioritize road sections that currently have a concentration of collisions. However, from a biological conservation perspective, direct road mortality may have already caused population depletion. This means that the greatest threat to population persistence due to direct road mortality may not always be along the road sections that currently have the highest concentration of dead individuals of the target species (Teixeira et al. 2017).
- Fences or other barrier types are the primary measure, as the primary purpose of fences along roads is to keep animals off the highway and reduce animal-vehicle collisions (Huijser et al. 2016a).
- Since fences alone would result in an absolute or near-absolute barrier for the target species, fences are typically combined with safe crossing opportunities for wildlife, especially wildlife crossing structures (underpasses and overpasses).
- The secondary function of the wildlife fences is to guide or funnel wildlife species to these crossing structures (Dodd et al. 2007, Gagnon et al. 2010).

If habitat connectivity for wildlife is the primary concern, then:

- Road sections where habitat connectivity needs to be maintained or restored are identified and prioritized. This may be based on the connectivity needs (genetic, demographic) for individual species (the "target species"), a wide suite of species or species groups, seasonal migration of certain species (e.g. for ungulates), dispersal to allow for colonization or recolonization of areas nearby or further away, or ecosystem processes in general (biotic and abiotic parameters), including those associated with climate change (e.g. Kramer-Schadt et al. 2004; Clevenger & Huijser 2011; Sawaya et al. 2013; 2014; Lister et al. 2015; Sawyer et al. 2016; Jarvis et al. 2018).
- While it seems logical to identify and prioritize road sections that currently have observations of animals living or moving close to the road and observations of animals crossing the road (both unsuccessfully and successfully), the greatest population level conservation benefit of reducing the barrier effect of a road may not be where most animals are currently. From the perspective of biological conservation at the population

level, areas where most animals are now may have high population viability, potentially despite being isolated because of the barrier effect of transportation infrastructure. In such cases, reducing the barrier effect does not necessarily lead to an increase in population viability. Instead, the greatest population level benefits of reducing the barrier effect can be where small and isolated populations can be made more viable by providing safe crossing opportunities. This may even include road sections that currently isolate unoccupied habitat patches, and that bisect planned habitat corridors rather than existing ones. In other words, crossing structures may also be required or can also be beneficial for population persistence in areas where the target species has low abundance or where it is currently entirely absent.

- Wildlife crossing opportunities, especially wildlife crossing structures, are the primary measure, as the purpose of wildlife crossing structures is to provide safe crossing opportunities.
- Crossing structures alone do not necessarily reduce collisions (Rytwinski et al. 2016). Therefore, wildlife crossing structures are typically combined with wildlife fences.
- An added benefit of connecting crossing structures to wildlife fences is that it guides or funnels wildlife to the crossing structures and that this increases the use of the structures (Dodd et al. 2007; Gagnon et al. 2010).

In this context, it is also important to be aware of the limitations of existing crossing structures that were not built for wildlife versus designated wildlife crossing structures. While designated wildlife crossing structures should be located where connectivity for wildlife is needed most, existing structures that were not built for wildlife are not necessarily located where connectivity for wildlife is needed most. Nor are such existing crossing structures necessarily of the right type (e.g. overpass vs. underpass) or dimensions given the target species, and there are typically limits to potential modifications to existing structures to improve the suitability for the target species. In conclusion, fences and wildlife crossing structures are almost always implemented together, regardless of whether the primary objective is to reduce animal-vehicle collisions or to reduce the barrier effect of roads and traffic for wildlife. However, the road sections where the measures are implemented are very much dependent on the primary objectives or departure points, and they may include road sections where the target species is not hit or no longer hit, and where the target species may have low population density or where it is currently not present at all.

3.2. Spacing of Wildlife Crossing Structures

The appropriate spacing of wildlife crossing structures can be determined in more than one way and is dependent on the goals one may have. Examples of possible goals are:

- Provide permeability under or over the road for ecosystem processes, including but not restricted to animal movements. Ecosystem processes include not only biological processes, but also physical processes (e.g. water flow). It is good practice to design structures that are primarily needed for hydrology in such a way that they can also function for wildlife. However, only providing wildlife crossing opportunities in low and wet areas means that no connectivity is provided for species that depend on high and dry habitat. Thus, a possible strategy is to identify the different ecosystems and habitat types (not just streams, rivers or wetlands) and ecosystem processes that permeability needs to be provided for and then provide appropriate mitigation measures in each of those ecosystems or habitat types.

- Allowing a wide variety of species, or selected targets species, to change their spatial distribution drastically, for example in response to climate change.
- Maintaining or improving the population viability of selected species based on their current spatial distribution. This includes striving for larger populations with a certain degree of connectivity between populations (including allowing for successful dispersal movements).
- Providing the opportunity for individuals (and populations) to continue seasonal migration movements (e.g. mule deer, pronghorn or elk) as this can be seen as a component of the biological integrity of an ecosystem.
- Allowing individuals of selected target species that have their home ranges on both sides of the highway to continue to use these areas. This may result in a road corridor that is substantially permeable to those species, at least for the individuals that live close to the road.

A further complication is that individuals that disperse, that display seasonal migration, or that live in the immediate vicinity of a road may display differences in behavior with regard to where and how they move through the landscape, how they respond to roads, traffic, and associated barriers (e.g. wildlife fencing), and their willingness to use safe crossing opportunities. For example, dispersing individuals may grow up far away from the areas adjacent to roads and may shy away from human disturbances and human made features, they may not move through habitat the way we might expect them to, and they typically travel long distances, much further and quicker compared to resident individuals. Safe crossing opportunities may not be encountered by dispersing individuals as they are new in the area and are not familiar with their location, and when confronted with a road or associated wildlife fence they may return or change the direction of their movement before they encounter and use a safe crossing opportunity. Furthermore, if dispersing individuals do encounter a safe crossing opportunity, they may be more hesitant to use it compared to resident individuals that not only know about their location, but that also have had time to learn that it is safe to use them. Since dispersal can be a relatively rare phenomenon, one may not be able to afford to have a dispersing individual fail to cross the road. Therefore, even though dispersers travel much further than resident individuals, safe crossing opportunities for dispersers may not allow for a greater distance between safe crossing opportunities compared to safe crossing opportunities for resident individuals.

Full scale population viability analyses can be very helpful to compare the effectiveness of different configurations of safe crossing opportunities. However, for this manual the authors choose a simpler approach and suggest the distance between safe crossing opportunities to be equal to the diameter of the home range of the species concerned (Figure 3). In theory, this allows individuals that have the center of their home range on the road to have access to at least one safe crossing opportunity. However, individuals that may have had their home range on both sides of the road do not necessarily have access to a safe crossing opportunity (Figure 4). Finally, this approach assumes homogenous habitat and distribution of the individuals and circular home ranges, while in reality habitat quality may vary greatly, causing variations in density and home range size of individuals and irregular shaped home ranges. Species that have smaller home ranges need the crossing structures to be closer together than species with large home ranges (Figure 3).

This approach does not necessarily result in viable populations for every species of interest, and that not every individual that approaches the road and associated wildlife fence, will encounter, and use a safe crossing opportunity. In addition, the approach described above is not necessarily the only approach or the approach that addresses the barrier effect of the road corridor and associated fencing sufficiently for all species concerned. However, the approach chosen is consistent, practical, can be based on available data, and is likely to result in considerable permeability of the road corridor and associated wildlife fencing for a wide array of species.

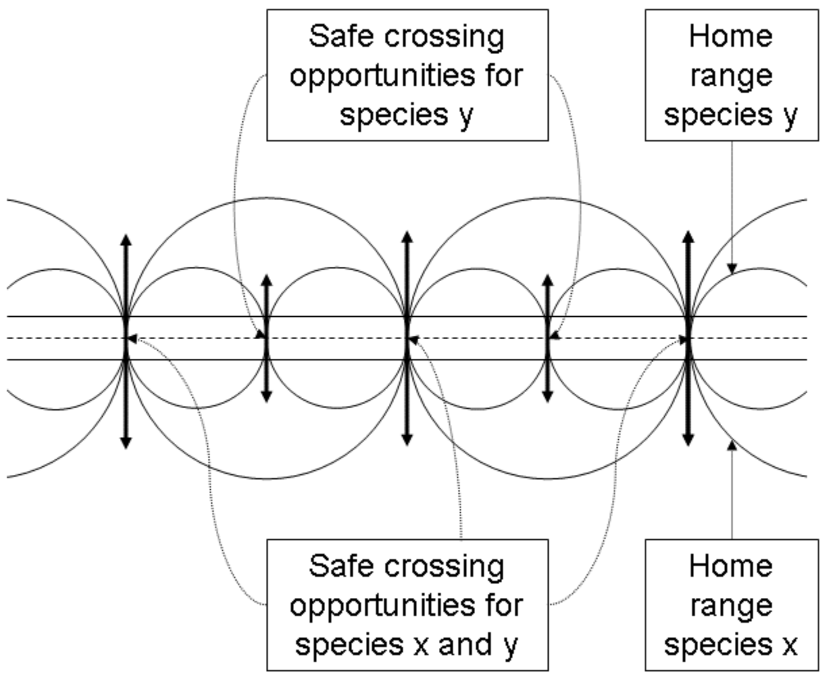

Figure 3. Schematic representation of home ranges for two theoretical species projected on a road and the distance between safe crossing opportunities (distance is equal to the diameter of their home range).

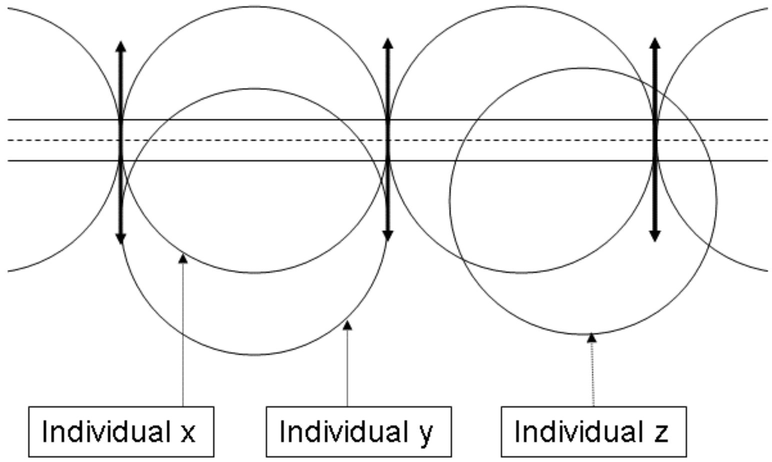

Figure 4. Schematic representation of home range for an individual (x) that has the center of its home range on the center of the road (access to two safe crossing opportunities), an individual (y) that has the center of its home range slightly off the center of the road exactly in between two safe crossing opportunities (no access to safe crossing opportunities), and an individual (z) that has the center of its home range slightly off the center of the road but not exactly in between two safe crossing opportunities (access to one safe crossing opportunity).

Another way to decide on "appropriate distance" between safe crossing opportunities is to evaluate what the spacing is for wildlife crossing structures on other wildlife highway mitigation projects. The average spacing for large mammal crossing structures in Montana (US Hwy 93 North and South), I-75 in Florida, SR 260 in Arizona, Banff National Park in Canada, and ongoing reconstruction on I-90 in Washington State is 1.2 mi (1.9 km) (range for the average spacing of structures in these individual areas is 0.5-1.8 mi (0.8-2.9 km)). However, the 1.2 mi (1.9 km) spacing is simply what people have done elsewhere, and it is not necessarily based on what may be needed ecologically, and the requirements for the target species in one area may be different from what is needed in another area.

3.3. Research and Adaptive Management

Without stating what the objective of the project is, without being able to verify whether this objective has been reached, we cannot ever know whether the project was a success, we cannot implement adaptive management, and we cannot apply lessons learned to a future project (Hardy et al. 2003).

Therefore, it is important to:

- Clearly define the objectives of a project. Associated parameters will likely relate to human safety, direct road mortality of wildlife, and habitat connectivity for the target species (van der Grift & Seiler 2016) (Figure 5).
- If one wants to know whether the objectives have been reached, then there should be a commitment to measuring the relevant parameters according to an appropriate study design.
- The objectives, target species and local conditions should inform the type, dimensions, and the locations of the crossing structures. Well designed and situated crossing structures are used by a many different animal species (e.g., Clevenger & Huijser 2011; Huijser et al. 2016b).
- If a new highway is constructed, the impact on wildlife connectivity and the effectiveness in reducing this impact should be compared to an area that does not have roads. If an existing highway is widened, the impact of the highway can be either compared to a roadless area or the existing highway before the widening took place. This is important as it relates to the reference for the effectiveness of the mitigation measures in reducing the impacts.
- Most studies that evaluate wildlife crossing structures simply count how many individual animals or what species use the structures over a certain amount of time. While wildlife use can often be described as substantial, these simple counts do not inform us about the effectiveness of the structures in relation to what animal movements were before a road was present or before a highway was widened. Very little information is available on true effectiveness of crossing structures, but they have been found to be "effective" in several studies. For example, when a highway is widened in combination with exclusion fences and wildlife crossing structures, connectivity of animal populations can remain similar or can even be improved compared to what it was before the highway widening (Huijser et al. 2016b). Exclusion fences and wildlife crossing structures can also increase the population size, increase gene flow, allow for seasonal migration, and improve population viability or population persistence of target species by reducing unnatural mortality and reducing the barrier effect of the transportation corridor (van der Ree et al. 2009; Sawyer et al. 2012; Sawaya et al. 2014).
- For many road ecology studies, a Before-After-Control-Impact (BACI) study design is a powerful way to answer questions related to the reduction in collisions, reduction in direct road mortality, and maintaining or improving habitat connectivity for wildlife (e.g. van der Grift et al. 2013). Note that obtaining "before" data may require research to start several years before implementing the measures and that suitable "control" road sections should also be included in the study design (Rytwinski et al. 2016). In some cases, expected benefits may be predicted or evaluated based on population viability modelling (e.g. van der Ree et al. 2009).

- The time required for research may start well before, and end well after, the period during which the mitigation measures are implemented. For habitat connectivity, there may even be a learning curve of at least several years, perhaps up to 5 to 10 years during which the animals learn about the location of wildlife crossing structures, that it is safe to use them, and during which the absolute use continues to increase (e.g. Clevenger & Barrueto 2014; Huijser et al. 2016b). In other words, wildlife use of wildlife crossing structures increases with the age of the structures, and one is more likely to reach objectives related to connectivity for wildlife 5-10 years after construction of the structure compared to the first few years.
- If research into effectiveness is an integral part of the construction project, the start and end dates of the project and associated funds may need to be based on the needs of the study design rather than the period during which implementation of the mitigation measures along the road takes place.
- If adaptive management is to take place, then the end date of a project, and the associated budget, may need to be extended even further. If adaptive management is required but if it lacks budget, it typically does not happen.

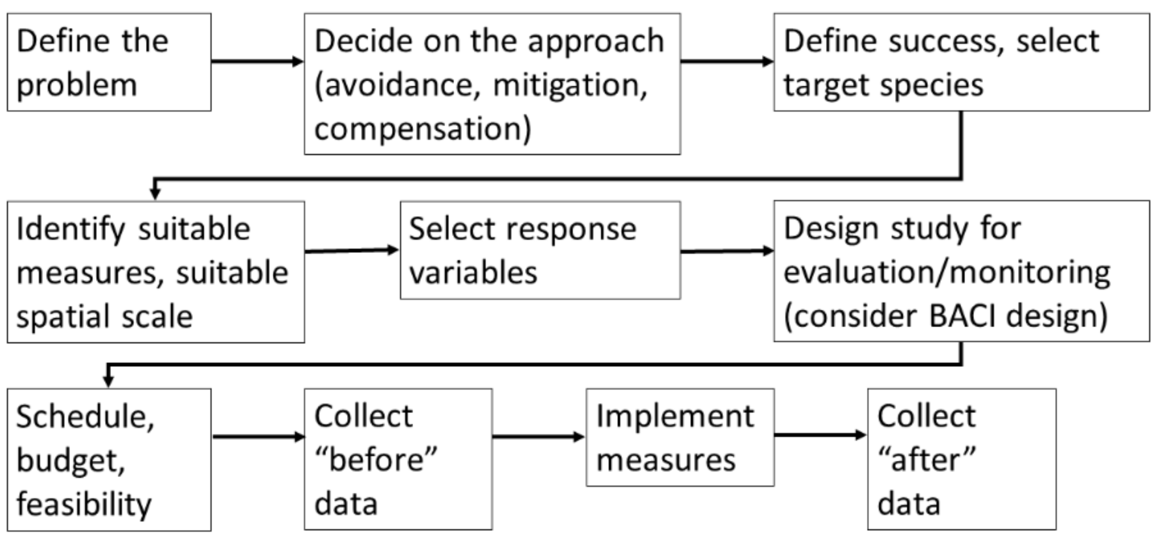

Figure 5. Flow charts of the steps that can be taken during the planning and design stages, as well during the research or monitoring stage.

4. SECTION A: LARGE WILD MAMMAL SPECIES

4.1. Introduction

This section relates to large wild mammal species. Specifically, North American large wild mammal species that have a body size and weight larger than a coyote (*Canis latrans*).

4.2. Wildlife Fences in Combination with Wildlife Crossing Structures

4.2.1. Planning and Design

4.2.1.1. Wildlife Fences or Other Barriers

- Before designing a wildlife fence or other barrier, decide on the “target species”. What are the species that need to be kept from entering the highway corridor?
- What is the goal? What constitutes “success” of the project? What is the objective or series of objectives? Can these objectives be made quantitative? Are they verifiable? Most likely, the success parameters of a project that includes fences or other barriers for large wild mammals include parameters related to reducing the number of collisions with large wild mammals and improving human safety.
- What are the “side-boards” of the project? Almost never would it be advisable or ethical to implement fences or other barriers without also providing for safe and effective crossing opportunities for wildlife (Moore et al. 2021). Maintaining or improving habitat connectivity for wildlife, potentially increasing population persistence in the surrounding landscape may be secondary objectives if the main concern is with human safety. However, secondary objectives are not necessarily optional; they may still be a requirement. There may also be “side-boards” related to engineering specifications, or even landscape aesthetics (Figure 6).

Figure 6. A barrier wall because of raised roadbed for wildlife underpass for Key deer (8 m wide, 3 m high), US Hwy 1, Big Pine Key, Florida, USA. A barrier wall can be considered if concerns for landscape aesthetics do not allow for a fence.

- Is the strategy to avoid, mitigate, or compensate the impacts of roads and traffic on wildlife? What is the ambition level? To what degree should the impacts be mitigated or compensated? On what spatial scale? Is the evaluation scale the project level (i.e. the road section that is to be mitigated), is it a longer road section (a combination of mitigated and unmitigated road sections, or is it on a landscape level where the overall impacts of a transportation network is addressed? The latter is more relevant when the success parameters are rooted in biological conservation, population ecology, or ecosystem integrity rather than human safety parameters. However, evaluation on a landscape level is more difficult, and perhaps only useful when action is also taken on a landscape level.
- Verify that wildlife fences or other barriers are indeed the most suitable measure given the target species and the stated objectives, the "side-boards", the strategy, and the ambition level. If the approach is "mitigation" rather than "avoidance" or "compensation", and if a road is to remain in place and permanently open for traffic, wildlife fences are generally considered the most effective mitigation measure for reducing wildlife-vehicle collisions (Rytwinski et al. 2016).
- Base the design of the barriers on the biological characteristics of the target species. The climbing, jumping, and digging capabilities of the target species as well as their strength (e.g. push or ram through fencing) needs to be considered. These species' characteristics influence fence height, the type of fencing material (e.g. mesh-wire, chain-link, electric), the type of post (wood, metal, concrete), the strength of the material, as well as specific features to discourage climbing (e.g. outriggers) or digging (dig barrier) (Table 1). Most "wildlife fences" in North America are 8 ft tall and have wooden posts and mesh wire fence with a mesh size of 6 x 9 inch (about 15x18 cm) (Figure 7). These wildlife fences

are not an effective barrier though for all large wild mammal species on the continent; most “wildlife fences” along highways are a substantial barrier to large ungulates, especially deer, elk, and moose. If other species are among the target species, the design of the fence may need to be different (Figures 8-10). Although it is good practice to identify the target species, it is also good practice to take a step back and look at the presence of other species in the area and how the proposed mitigation measures may positively or negatively impact them and make adjustments that go beyond the minimum design that is required for the target species. Note that the design characteristics summarized in Table 1 are indicative only; they are not necessarily prescriptive, and the practices – effective or not - are varied (Huijser et al. 2015a) The main purpose of this table is to illustrate how the biological characteristics of a target species have consequences for the design specification of a fence or other barrier. High-tensile top wires can both limit the damage to the fence from of fallen trees and increase the rigidity of the fence (Figure 11). For this table we especially suggest high-tensile top wire in areas with trees.

Table 1: Indicative fence characteristics for selected potential wild large mammal target species in North America. Note that fence height may have to be adjusted if the fence is positioned on a slope.

Target species	Fence height	Posts	Fence material	Dig barrier	Overhang	High tensile top wire*7
White-tailed deer, mule deer, elk, moose	8 ft (2.4 m)	Wood	Mesh-wire	No	No	Yes
Pronghorn*1	5 ft	Wood	Mesh-wire	No	No	No
Bighorn sheep	10 ft	Wood	Mesh-wire	No	Yes	Yes
Mountain goat	8 ft	Wood	Mesh-wire	No	No	No
Bison*6	6-7 ft	Wood	High-tensile strand or mesh-wire	No	No	No
Caribou						
Black bear*2	10 ft	Metal	Chain-link	Yes	Yes	Yes
Grizzly bear*3	8 ft	Wood	Mesh-wire	Yes	No	Yes
Mountain lion*4	12 ft	Metal	Chain-link	Yes	Yes	Yes
Wolf*5	8 ft	Wood	Mesh-wire	Yes	No	Yes

*1 Pronghorn almost never jump fences, but they will try to crawl under or through a fence.
*2 Black bear can climb wooden posts and insert their feet in large mesh size of mesh-wire fence. Tall fence, metal posts, fence material with small mesh size (e.g. chain-link), fence overhang, and dig barriers are recommended. Strands of electrified wire can further increase functionality of the barrier.
*3 Grizzly bears are not likely to climb a fence, but a dig barrier is recommended
*4 Mountain lions are good climbers and jumpers. Very tall fence, metal posts, small mesh sizes, and overhang is recommended
*5 Wolves are very good diggers; a dig barrier is recommended.
*6 Bison are strong and given enough motivation can breach through fences. Fences should be strong and visible. Strands of electrified wire can further increase functionality of the barrier.
*7 Especially recommended in areas with trees where a tree may fall on the fence.

Figure 7. Typical large ungulate fence in North America, 8 ft tall, wooden posts and mesh-wire fence material, US Hwy 93 North, Montana, USA. Note that there is a dig barrier attached to the main fence material (e.g. for canids).

Figure 8. Fence for Florida panther (*Puma concolor coryi*), 10 ft tall, metal posts, chain-link fence material, and overhang, SR 29, Florida, USA).

Figure 9. Outrigger on a fence for Florida panther (*Puma concolor coryi*), SR 29, Florida, USA. Note that the outrigger faces the safe side, the habitat side of the fence.

Figure 10. Wildlife fence and dig barrier ("buried fence" or "apron"), Trans-Canada Highway, Banff National Park, Alberta, Canada. The dig barrier in the soil angles (45°) towards the safe side or habitat side; it angles away from the fence and the road on the other side (Clevenger and Huijser 2011). The dig barrier keeps animals from digging under the fence. The dig barrier may consist of a 4-5 ft (1.0-1.2 m) wide galvanized chain-link fence that is attached to the bottom of the actual fence. The buried fence should extend approximately 3.5 ft (1.1 m) under the ground (Clevenger and Huijser 2011).

Figure 11. Wildlife fence with high-tensile top wire to reduce damage from falling trees, Trans-Canada Highway, Banff National Park, Alberta, Canada.

- There may be multiple target species, perhaps even from entirely different species groups. This may result in a combination of different types of fence material. Fence materials may include plastic sheeting for amphibians, reptiles, and small mammals at the bottom, and mesh-wire fencing with smaller mesh size sizes for medium sized mammals higher up, and larger mesh size towards the top of the fence (Figure 12).

Figure 12. Wildlife fence for amphibians (e.g. common toad (*Bufo bufo*)), medium sized mammals (e.g. Eurasian badger (*meles meles*)) and large ungulates (e.g. roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*)) at ecoduct Woeste Hoeve A50 near Apeldoorn, The Netherlands.

- Use material (fence posts, fencing material) that is consistent with the environment. For example, rocky roil may require metal posts rather than wooden posts (Figure 13). Sedimentation and erosion processes can also influence the choices of material.

Figure 13. Wildlife fence with metal posts as a barrier for deer (*Odocoileus* spp.) and elk (*Cervus canadensis*) along SR 260, east of Payson, Arizona, USA. Some of the metal posts are set in concrete.

- Use material (fence posts, fencing material) that is consistent with the desired lifespan of the fence. Standard large ungulate fencing in North America (wooden posts, mesh wire fence material) is projected to last 25 years (Huijser et al. 2009).
- Minimize the number of access points for side roads and trails along a fenced road corridor. Each access point is a potential weak spot where animals may enter the fenced road corridor.
- Wildlife fencing should cover the road length that may have a concentration of wildlife-vehicle collisions with the target species (i.e. "hotspots") and adjacent buffer zones to keep the animals from simply crossing the highway at the fence ends (Ward 1982; Huijser et al. 2015a). The length of the buffer zone is at least partially influenced by the home range size of the target species. For white-tailed deer in North America 1 km long buffer zones have been suggested (starting from each end of the hotspot) (Huijser et al. 2008b). Note that fences may need to be implemented over long distances if the objective is to reduce the overall number of collisions rather than just reduce the number of collisions in the fenced road section (Huijser & Begley 2022).

- When designing wildlife fencing (in combination with safe crossing opportunities for wildlife) consider implementing the fencing over at least 3 miles (5 kilometers) of road length rather than at shorter road sections (Huijser et al. 2016a).
- Almost always, install wildlife fencing on both sides of a highway, not only on one side (Clevenger & Huijser 2011).
- Almost always try to have the wildlife fencing start and end points on opposite sides of the highway aligned directly across from each other, rather than in an offset or staggered pattern (Clevenger & Huijser 2011).
- Almost always, include wildlife crossing opportunities that are suitable for the target species, and consider the needs of other species in the area, especially those that are not a target species but for which the fence may also result in a barrier. Solving one problem (direct road mortality, human safety) should not cause another problem (barrier effect for wildlife) (Moore et al. 2021).
- During the planning and design process, continuously check if the stated objectives are likely met through implementing the proposed measures. For example, while it seems obvious that fences at least cover the full length of the road section with a concentration of collisions (and also an adjacent buffer zone), landscape aesthetics, the number of access points, the costs of mitigating these gaps in the fence (e.g. with wildlife guards or electrified mats), and potential opposition from adjacent landowners may result in a pushback against fences and not having fences cover the full length of a hotspot and adjacent buffer zones (see e.g. Cramer et al. 2014). When there is a discrepancy between the stated objectives and the proposed mitigation measures, either adjust the objectives or the proposed measures. Proceeding with a discrepancy between the stated objectives and the proposed measures almost certainly leads to failure of the project.
- High quality research is expensive and takes time. Therefore, it is essential that researchers and the experimental design take part in the project discussions from the earliest phases onwards (Rytwinski et al. 2015).

4.2.1.2. Wildlife crossing structures

- Before designing a wildlife crossing structure (i.e. an underpass or overpass), decide on the "target species". What are the species that need to move from one side of the road to the other?
- What is the goal? What constitutes "success" of the project? What is the objective or series of objectives? Can these objectives be made quantitative? Are they verifiable? Most likely, the success parameters of a project that includes wildlife crossing structures for large wild mammals include parameters related to wildlife movement through or across these structures. At the most basic level, wildlife use is what needs to occur; without wildlife use the structure fails to function. But how much use do we need to see to before we call the implementation of a wildlife crossing structure a success? A use "number" may or may not have much relevance for how much the barrier effect of a road and traffic is reduced, and whether that is sufficient for species and individuals that live adjacent to the road, or that need to cross a road because of seasonal migration or dispersal. Effectiveness of wildlife crossing structures is a complex concept that can be hard to define and measure (van der Grift et al. 2015). However, examples of

effectiveness parameters are potential benefits of the mitigation measures to population survival probability of a species in the surrounding area, maintaining or restoring genetic connectivity, maintaining, or restoring seasonal migration movements, or allowing for successful dispersal of individuals that can strengthen small and isolated populations of that species elsewhere. In some cases, such small and isolated populations may have been extirpated already and improved connectivity across roads may allow for recolonization.

- Note that the objectives may not only be related to one or several target species. The objectives can also be related to a broad suite of species across multiple animal species groups, including small species groups such as invertebrates, amphibians, reptiles, and small mammals. The objectives may also relate to maintaining or restoring ecosystem processes that include both biotic and abiotic components. Finally, the objectives may also be related to addressing the impacts of climate change where entire ecosystems may need to shift spatially. Some of these impacts may need to be addressed already, whereas others may be expected in the future, but within the lifespan of the wildlife crossing structure.
- What are the "side-boards" of the project? Must the project also lead to fewer wildlife-vehicle collisions and must there also be a benefit for human safety? If so, then wildlife crossing structures should be combined with wildlife fences. Crossing structures alone do not reduce wildlife-vehicle collisions, but wildlife crossing structures in combination with wildlife fences do (Rytwinski et al. 2016). In addition, the use of a wildlife crossing structure that is connected to wildlife fences increases (Dodd et al. 2007; Gagnon et al. 2010). Another type of side-board is where wildlife crossing structures are and are not considered. Ideally, wildlife crossing structures should be located where connectivity for wildlife leads to the greatest conservation benefits, e.g. increased population survival probability, maintaining or restoring seasonal migration, and allowing for daily movements of animals that have their home range on both sides of a road. However, crossing structures are more likely to be considered where the adjacent land is likely to remain good wildlife habitat (protected areas, private land with conservation easement), where there is suitable topography (e.g. a road-cut for a wildlife overpass, a road-fill for an underpass), or streams and rivers that already require a culvert or bridge for hydrological reasons.
- Base the location and number of structures on the objectives (see above). Population viability and wildlife movement modelling are useful tools for comparing the effectiveness of providing safe crossing opportunities in different locations and numbers.
- Base the type (e.g. underpass or overpass), the approach slope, the dimensions (e.g. width, height) and the associated habitat inside or on top of the crossing structure on the biological requirements and behavior of the target species as well as the surrounding landscape (Tables 2, 3). Different species are more or less likely to use certain types and dimensions of wildlife crossing structures. For a crossing structure type and dimension to be considered suitable for a species, the likelihood that the structure will be used by an animal that approaches a structure should be "high". While there are no established minimum norms for acceptance, selecting a structure type and dimensions that have a high acceptance rate (perhaps at least 70-80%) for the target species seems logical. In this context it is important to remember that having observed "use" by a species does not mean that it is defensible to claim that that that structure type and its associated dimensions are "suitable", as a structure with a very low acceptance rate still has some

"use". By definition, a crossing structure that is "suitable" for the target species is much more likely to be found effective in reaching objectives related to the connectivity than a crossing structure that may be "used" but that may not have a high acceptance rate. Data on acceptance (and thus suitability) are not common (but see e.g. Purdum 2013; Huijser et al. 2019; Denneboom et al. 2021), and they are not available for all large mammal species in North America. Instead, we summarize the suitability of different types of crossing structures and dimensions based on data analyzed by the authors, supplemented by their interpretation of the literature and their opinion (Table 3). The approach slope of a crossing structure likely also influences the acceptance of a structure by wildlife. While data on this parameter are not available, the authors of this report suggest a very gradual approach to an underpass and overpass (perhaps 10-15% at a maximum). This may be especially relevant in open and flat landscapes compared to landscapes with lots of cover and topography. Gradual approaches may impact natural vegetation. However, the vegetation on the approaches may be restored after construction, and the disturbance is only once. The structure itself may only have a lifespan of 75-80 years (Huijser et al., 2009). Therefore, the soil and vegetation on top of an overpass or at an underpass may be disturbed each time the structure is replaced.

Table 2: Crossing structure types and dimensions.

Safe Crossing Opportunity type	Indicative dimensions (as seen by the animals)	Image
Wildlife overpass	50-70 m wide	
Open span bridge	12-30 m wide, ≥5 m high	
Large mammal underpass	7-8 m wide, 4-5 m high	

Safe Crossing Opportunity type	**Indicative dimensions (as seen by the animals)**	**Image**
Medium mammal underpasses	0.8-3 m wide, 0.5-2.5 m high	
Small-medium mammal pipes	0.3-0.6 m in diameter	

Table 3. Suitability of different types of mitigation measures for selected large mammal species (for 2-3 lane highways [25-35 m (82-115 ft)] wide road without median).
1 Recommended/Optimum solution; 2 Likely, but no data, 3 Likely marginal or somewhat possible if adapted to species' specific needs; 4 Not recommended; 5 Unknown, more data required; — Not applicable (Clevenger & Huijser 2011, O'Brien et al. 2013, Ford et al. 2017, Huijser et al., preliminary data; Clevenger, unpublished data).

	Wildlife overpass	Open span bridge	Large mammal underpass	Medium mammal underpass	Small-medium mammal pipes
Mountain lion	1	1	1	4	4
Wolf	1	1	3	4	4
Deer spp.	1	1	1	4	4
Elk	1	1	3	4	4
Moose	1	1	3	4	4
Pronghorn	1	3	4	4	4
Bighorn sheep	1	1	1/3	4	4
Mountain goat	1	1	3	4	4
Caribou	2	2	5	4	4
Bison	2	2	5	4	4
Black bear	1	1	1	4	4
Grizzly bear	1	1	3	4	4

- Crossing structures are usually built with concrete and steel. However, overpasses can also be constructed out of other materials that may reduce the CO2 output, have longer lifespan, and would allow for a modular structure that may be disassembled and moved should wildlife change where they approach the road (e.g. in response to development) (Bell et al. 2020).
- Avoid dividing walls or pillars inside a structure; make the structure as open as possible to allow wildlife to see the sky and vegetation on the other side of the structure.
- The number of wildlife crossing structures, or the spacing between them, depends on the objectives and how much movement of the target species is needed to reach those objectives. This is often difficult to determine, and it may require substantial modelling that requires data and a series of assumptions. An alternative approach would be to calculate the home range size of the target species (see section 3.2).
- Consult with engineers about the soil stability and ground water levels in the surroundings of potential sites for wildlife crossing structures. Soil stability and ground water level can impact site selection and design.
- Where there is a median, separate structures may be required for the two travel directions. Design these structures as a pair with one continuous line of sight to the area on the other side of the road.
- Consider ponds or water holes on either side of a crossing structure to attract wildlife to the structure (Figure 14).

Figure 14. Wildlife pond at the approach of wildlife overpass "Groene Woud" across A2 motorway, The Netherlands.

- The soil and vegetation on top of wildlife overpasses should be similar to that of the surrounding area. In some cases, one may choose to engineer a variety of habitat types on an overpass (e.g. cover, edge habitat, open areas). Choose soil depth and associated water retention carefully as it allows or does not allow for shrubs and trees, and the weight likely has design consequences for an overpass (Figures 15-16). Use native soil and do not introduce non-native invasive species.

Figure 15. Shrubs and trees on a wildlife overpass, Ruta 101, Misiones, Argentina.

Figure 16. Cover and open habitat on top of multifunctional overpass (farm road and wildlife, about 100 m wide), across A4 motorway, Parndorf, Austria. The overpass is designed for farmers, agricultural machinery, hunters and wildlife including roe deer (*Capreolus capreolus*) and European hare (*Lepus europaeus*).

- If crossing structures not only need to provide connectivity for large wild mammal species, but also for small wild animal species (see Section C), then appropriate habitat should be provided for these small animal species as well. Because of slow travel speed and short travel distances, small animal species may require everything they need during their life at a wildlife crossing structure (e.g. water, food, cover)
- Light and noise from vehicles can be reduced through berms and solid fences (e.g. planks) on the two sides of a wildlife overpass, or along the road above an underpass (Figures 17-20). Light and noise barriers can be combined with a wildlife fence.

Figure 17. Visual barrier combined with large mammal fence on an overpass, The Netherlands.

Figure 18. Berm on wildlife overpass "Groene Woud" across A2 motorway, The Netherlands. The berm with rootwads and shrubs provides cover on either side and reduces visual and noise disturbance barrier combined with large mammal fence on an overpass, The Netherlands.

Figure 19. Visual barrier above a wildlife underpass, Amersfoortseweg, Hoog Soeren, The Netherlands. The fence reduces visual and noise disturbance from traffic for the animals that approach the underpass.

Figure 20. Visual barrier on a multifunctional underpass (water, wildlife), The Netherlands. The fence reduces visual and noise disturbance from traffic for the animals that approach the underpass.

- While some people have expressed concern about wildlife crossing structures acting as a prey trap, there is no evidence that predators select wildlife crossing structures to hunt (Ford & Clevenger 2010).
- In general, try to minimize human presence and disturbance at and near wildlife crossing structures (e.g. no human co-use, no hunting, no cutting of trees or other vegetation, no frontage or other roads near the approaches, no street lights). Large boulders or tree trunks at structure entrances can be used to discourage motorized use of the structures (Figure 21). Native, natural, and undisturbed habitat at and near the crossing structures is especially important for rare and sensitive species.

Figure 21. Boulders block access to unauthorized vehicles at wildlife underpass, US Hwy 95, Chilco, Idaho, USA.

- For a bidding process, try not only including engineering specification but also ecological specifications to increase the probability that the structure will function as intended for wildlife species.
- In multi-functional landscapes with common species that are accustomed to a certain level of human disturbance, one may consider combining wildlife use and non-motorized human use (e.g. pedestrians, bicyclists, equestrian use) (Figure 22). In general, human co-use pushes wildlife use to the dark hours, but one should be careful with widespread implementation until better data are available (van der Ree et al. 2015). It may be advantageous to have a strategic partnership with other stakeholders (e.g. non-motorized recreational interest groups), potentially allowing for a greater number of structures to be built with an overall better outcome for wildlife connectivity. If human co-use is desired, place the path for humans on one of the outer sides of a structure, and minimize human presence and disturbance to other areas of the structure, e.g. through a berm, trees and shrubs places between the path and the area designed for wildlife.

Figure 22. Hiking and biking trail combined with wildlife overpass across railroad tracks, Soest, The Netherlands. The "wildlife area" on the overpass is further to the left, separated from the trail by a berm and shrubs and trees.

- Crossing structures originally designed for other purposes (e.g. water), should have a path for large wild mammals that is at least 8 ft (2.4 m) wide and they should have a clearance of at least 13 ft (4 m) (Clevenger & Huijser, 2011) (Figure 23).

Figure 23. Pathway for large mammals in an underpass (bridge) primarily designed for water (stream), US Hwy 93 S, Bitterroot Valley, Montana, USA.

- For rivers and streams, bottomless structures are recommended. This allows for natural substrate and stream dynamics (Figure 24).

Figure 24. Bottomless multifunctional underpass, Hwy 88 near Jackson, California, USA. The underpass is for a creek (hydrology) and wildlife (e.g. mule deer).

- If culverts or other structures are used that have a "bottom" consider placing native soil on the bottom (Figure 25). Note that that may not be possible if the crossing structure also has flowing water.

Figure 25. Multi-functional underpass for wildlife and water with soil and rocks that cover the bottom of the culvert, US Hwy 93, near St Ignatius, Flathead Indian Reservation, Montana, USA.

4.2.1.3. Fence-ends

- Suggestions for the appropriate fence length and thus the location of fence-ends are discussed under “wildlife fences”. “Fence-end runs” are situations where animals cross the road in high numbers at or near fence-ends (Figure 26). Such fence-end runs are best addressed by having the fence-end at appropriate locations, well away from known movement areas or suitable habitat.

Figure 26. Wildlife trail at a fence-end, US Hwy 95, Bonners Ferry, Idaho, USA. This is an indication that there is a concentration of wildlife crossings at the fence-end (a "fence-end run"), potentially resulting in a concentration of collisions at or near the fence-end, just inside or just outside the fenced road section.

- Fence-end treatments are especially important if the fenced road length is relatively short (e.g. shorter than 3 mi (5 km) (Huijser et al. 2016a). The effectiveness of short sections of wildlife fencing is substantially reduced by collisions inside the fenced road section at or near fence-ends. While these collisions also take place at fence-ends associated with longer fenced road sections, they have limited consequences for the overall effectiveness of long fenced road sections (Huijser et al., 2016a). Be careful and don't assume that steep rocky slopes or other landscape features are a barrier for the target species; animals will often move over difficult terrain when forced or motivated.
- To reduce the likelihood of animals accessing the fenced road corridor at a fence-end, consider bringing the fence-ends close to the edge of the pavement (Figure 27). Note that a split fence-end is possible where the other fence-end angles away from the road. Boulder fields at fence-ends have also been used to discourage ungulates from accessing the fenced road corridor by walking and grazing in the right-of-way (Figure 28). Note that boulder fields are likely less effective for species with paws.

Figure 27. Fence-end brought close to the edge of the pavement, protected by Jersey barriers. Also note that there is a wildlife guard embedded in the travel lanes, Alberta, Canada.

Figure 28. Boulder field at a fence-end, Alberta, Canada.

- Consider implementing wildlife guards (similar to cattle guards) or electric mats embedded in the roadway to reduce wildlife intrusions into the fenced road corridor at fence ends and at access roads (Figures 29-31). Wildlife guards or “cattle guards” may be a substantial barrier to ungulates, but not to species with paws (Allen et al. 2013). For species with paws, including bears, canids and felids, electrified barriers may be required.

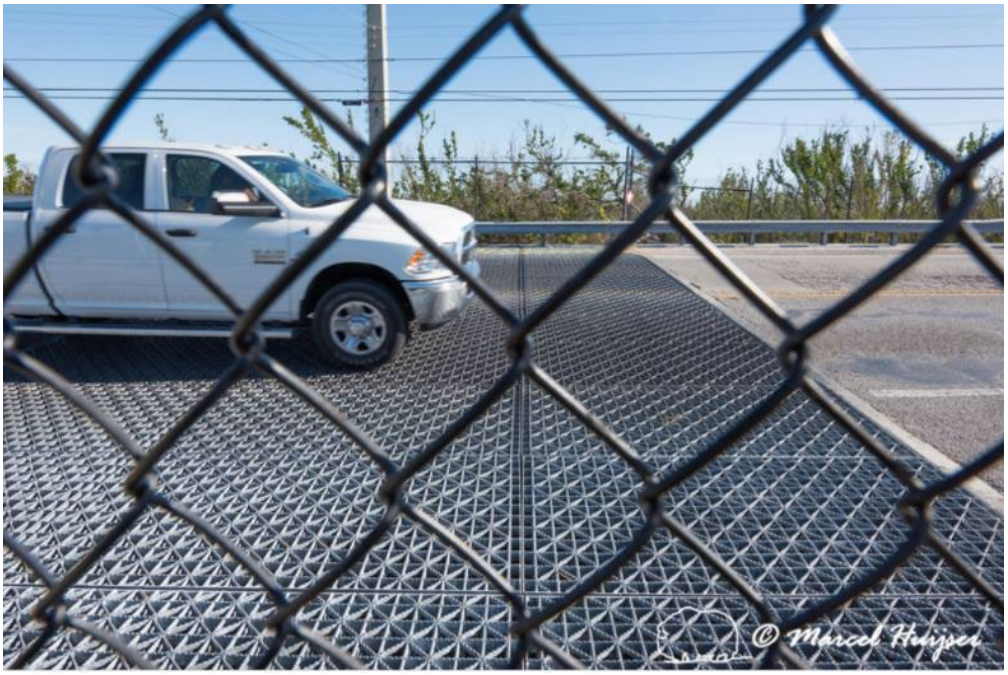

Figure 29. Wildlife guard at a fence-end on US Hwy 1, Big Pine Key, Florida, USA.

Figure 30. Electrified mat associated with an animal detection and driver warning system at a fence-end, S.R. 260 east of Payson, Arizona, USA.

Figure 31. Electrified barrier embedded in travel lanes to keep large mammals, including bighorn sheep, out of fenced road corridor, MT Hwy 200, Thompson Falls, Montana, USA.

- To further reduce the likelihood of animals getting on the road at or near a fence-end, consider angling the fence away from the road at the fence-end. This may encourage animals to turn back into the surrounding area, walk back along the fence and potentially find and use a suitable wildlife crossing structure, or it may result in them crossing the road further away from the fence-end. Note that a split fence-end is possible where the other fence-end angles towards the road.

4.2.1.4. Access points

- Similar to fence-ends, access points result in gaps in the fence. Wildlife guards and electrified barriers can also be used at access roads, but, in contrast to the main travel lanes at fence-ends, they may be designed for lower traffic volume and lower vehicle speed (Figures 32-33). Wildlife guards or “cattle guards” may be a substantial barrier to ungulates, but not to species with paws (Allen et al. 2013). For species with paws, including bears, canids and felids, electrified barriers may be required, sometimes in combination with a wildlife guard (Figure 34).

Figure 32. Wildlife guard installed at an access road to the main highway (US Hwy 93S), near Stevensville, Montana, USA. The metal barrier is easy to walk and bike over. Note that the concrete ledge can be used by wildlife to access the fenced road corridor. This concrete ledge should be made inaccessible.

Figure 33. Wildlife guard at an access road to US Hwy 93S, near Victor, Montana, USA. This type of wildlife guard is less suited for pedestrians and cyclists.

Figure 34. Electrified barrier, designed for low traffic volume and low traffic speed, on top of a wildlife guard at an access road to US Hwy 93S, near Ravalli, Montana, USA.

- Wildlife should not be able to bypass a wildlife guard or an electrified mat. The fence should run tight along the sides of the barrier. In the image below, the concrete ledge (i.e. the wall of the pit under the barrier), has been made inaccessible to large mammal species (Figure 35).

Figure 35. Blocked concrete edge at side of wildlife guard at access road US Hwy 93, Arizona, USA. Some wildlife species will walk on the narrow concrete edge of the wildlife guard to access the fenced road corridor. The concrete edge is part of a wall for the pit under the metal bars. Here the edge is made inaccessible to large mammals through an extra piece of wildlife fence.

- Allow small animal species that fall in the pit under a wildlife guard to escape (Figures 36-37). Exits may be provided at the sides, or through an escape ramp, although the effectiveness of escape ramps is not known.

Figure 36. Combined drainage and escape for small animals under wildlife guard, Arizona, USA. The openings on the side allow for drainage under the culvert. The openings also allow invertebrates, amphibians, reptiles, small mammals and other species that may fall in between the metal bars to escape.

Figure 37. For wildlife guards that have a fully enclosed pit with contiguous walls sometimes wooden planks or metal strips are attached, potentially allowing small animal species to climb out of the pit.

- Wildlife guards can be designed to be more friendly to pedestrians and cyclists (Figures 38-40).

Figure 38. Bicyclist on wildlife guard for wild boar (*Sus scrofa* and moeflon (*Ovis orientalis*) at a bicycle path, National Park Hoge Veluwe, The Netherlands. This wildlife guard has an escape ramp for small animals that fall into the pit under the metal grate.

Figure 39. Detail of the modified bridge grate material used for wildlife guards installed at access roads along US Hwy 93, near Ravalli, Montana, USA. This material is more suitable for pedestrians and cyclists compared to the bars of a traditional wildlife guard or cattle guard.

Figure 40. Push button on timer (turns electricity off for 1 minute) for pedestrians at an electrified barrier embedded in travel lanes to keep large mammals, including bighorn sheep, out of fenced road corridor, MT Hwy 200, Thompson Falls, Montana, USA.

- For non-motorized traffic, swing gates may also allow for access to and from the fenced road corridor (Figure 41-43).

Figure 41. Swing gate at a wildlife fence, set at an angle so it closes through gravity, The Netherlands.

Figure 42. Wildlife guard (right) and horse gate (left), Heugterdijk, Weerterbos, near Maarheze, The Netherlands. The riders do not have to dismount and can push the rotating gate while in the saddle. The gate is set at an angle so that gravity will bring the rotating fence in line with the main fence.

Figure 43. Pedestrian gate with steps (for high snow accumulation) at a wildlife fence, Alberta, Canada.

4.2.1.5. Jump-outs or escape ramps

- Consider implementing jump-outs (or escape ramps) to allow animals that get caught in the fenced road corridor to escape to the safe side of the fence (Figures 44-49). A jump-out should be low enough for animals to readily leave the fenced road corridor. At the same time, the jump-out should be high enough so that animals do not readily jump into the fenced road corridor.
- While widely implemented, little is known how well or how poor wildlife jump-outs or escape ramps function. The appropriate height depends on the jumping and climbing capabilities of the target species. Since there is often more than 1 target species, there is no one recommended height. However, jump-outs for deer may need to be around 5 ft high and for elk around 6 ft. A bar on top of the wildlife jump out can help reduce the likelihood that animals will jump into the road corridor. Animals that want to jump down can first step over the bar and take advantage of the low height of the wall of the jump-out.
- The face of the jump-out can consist of rocks, concrete blocks, wooden planks or other material. In general, it is advisable that the face is smooth to discourage animals from climbing the wall. The face can even be a metal plat (e.g. to discourage bear species from climbing the jump-out into the fenced road corridor.

Figure 44. Wildlife jump-out or escape ramp with a rock wall and bar designed for desert bighorn sheep (*Ovis canadensis nelsoni*), US Hwy 93, Arizona, USA. The bar reduces the probability that bighorn sheep will jump up into the fenced road corridor while it does not decrease the probability that the bighorn sheep will jump down to the safe side of the fence. The sheep can crawl under the bar before jumping down.

Figure 45. Wildlife jump-out with concrete blocks and a bar for bighorn sheep (*Ovis canadensis*), near Thompson Falls, Montana, USA. Note that it is probably better to not have the concrete blocks protrude as it makes it easier for species to climb the face.

Figure 46. Wildlife jump-out along US Hwy 93, Flathead Indian Reservation, Montana, USA. Jump out is 5 ft tall with rebar on top.

Figure 47. Wildlife jump-out with a smooth metal face to reduce the likelihood that bear will climb the jump-out and end up in fenced right-of-way, Banff National Park, Alberta, Canada.

Figure 48. Wildlife fence and jump-out with a face consisting of wooden planks, near Havre, Montana, USA.

Figure 49. Wildlife fence and jump-out along A28 motorway, near Spier, Drenthe, The Netherlands. The fence is a barrier for medium and large mammal species. The electric fence is an additional barrier for livestock (sheep, cattle) that are used as a tool for nature management in the area.

- While many jump-outs have a short perpendicular fence on top, its potential benefits or lack thereof are not known (Figure 50).

Figure 50. jump-out for bighorn sheep (*Ovis canadensis*) with a short perpendicular fence, near Thompson Falls, Montana, USA. The potential benefits of the perpendicular fence in guiding wildlife to the jump-out are not known.

4.2.2. Implementation/Construction

4.2.2.1. Wildlife Fences or Other Barriers

- Make sure that no gaps remain where the fence connects to the ground. If a dig barrier is added, such gaps not a concern (Figure 51).

Figure 51. Wildlife fence does not connect to the ground, Arizona, USA. Animals may be able to crawl under the fence.

- Make sure no gaps or other weak points in the fence occur because of installation errors or challenges. Gaps are especially common where the fence connects to the wingwalls of underpasses or the walls of jump-outs, or to gaps in the fence at access roads (Figures 52-53). The fence not only needs to have the end-post have a tight connection with the wingwall of an underpass or the wall of a jump-out, but if the fence runs parallel to the wingwall, it must also have a tight connection with the wingwall everywhere they run parallel. A "wedge" or "funnel" between the wingwall and the fence can encourage animals that want to escape the fenced right-of-way to enter the wedge or funnel and get trapped, potentially resulting in injury or death. Alternatively, the fence comes in at an angle that is more perpendicular to the of the wingwall of the structure, and then the danger of animals getting trapped between the wingwall and the fence is also addressed. The end-post of a fence should be located where the wall is at least as high as the fence itself. If the end-post is located where the wall is lower than the fence, the "exclusion system" falls below the design specifications. Gaps in the fence at access roads may require wildlife barriers such as wildlife guards (see later).

- Have a road ecologist oversee fence installation to reduce the likelihood of installation errors. Once installed, installation errors are hard and expensive to correct, or the errors may never be corrected at all. This can severely jeopardize the effectiveness of the mitigation measures.

Figure 52. Tight connection (no gap) between last fence post and wall of the wildlife underpass, Hwy 331, Hwy 83 near Freeport, Florida, USA. The angle at which the fence comes in does not result in a dangerous wedge or funnel that could lead to animals getting trapped.

Figure 53. Mule deer (*Odocoileus hemionus*) got stuck between wildlife fence and the wing wall associated with a wildlife underpass and dies, Montana, USA. The fence should be snug up to the wing wall. Here the last fence post was close enough to the wing wall but the second to last post allowed for a funnel like configuration making the deer believe it could potentially pass in between the wall and the fence. When it realized it could not go forward anymore it tried to turn itself around and then got stuck and died. It is important that both the post and the fence are positioned such that no space is left between the wing wall and the fence.

4.2.2.2. Crossing structures

- It is possible to minimize vegetation removal and soil and hydrology impacts during the construction of a bridge (Figure 54). It requires restrictions for where machines and personnel can go. In the case of the desert vegetation under the bridge in Arizona it may take many hundreds of years for the vegetation to recover after a disturbance. Given the fact that a bridge may only have a life span of 75 years, the vegetation under the bridge would never have a chance to recover. Therefore, it makes sense to minimize impacts to the vegetation and soil to begin with.

Figure 54. Bridge shortly after construction, Tonto National Forest, Arizona, USA. Note that the impacts of the construction on the vegetation and soil have been minimized.

- A tight connection between crossing structures and the wildlife fence is essential.
- Erosion and sedimentation control measures need to be put in place at steep slopes and low-lying wet areas, especially with flowing water (Figure 55). Use natural products that decompose (Figure 56). Do not use plastic or nylon netting as animals may get entangled and die.

Figure 55. Erosion control at a construction site of new bridge in association with highway widening (4 lanes to 2 lanes), Hwy 331, Hwy 83 near Freeport, Florida, USA.

Figure 56. Straw fiber rolls to control erosion on a road cut, Hwy 87, Arizona, USA.

4.2.3. Operation and Maintenance

4.2.3.1. Wildlife Fences or Other Barriers

- Implement fence inspection and maintenance programs, including for damages to the fence because of vehicles that have run off the road, fallen trees or rock fall, trees, vines and other vegetation growing on, over, and through fences, and erosion and sedimentation processes.
- Fence maintenance is typically not a priority for road maintenance crews. Therefore, consider including maintenance requirements in contracts with toll road companies, or outsource fence inspection and maintenance along state and federal highways. Without effective fence maintenance, wildlife fences typically become ineffective quickly. This can severely jeopardize the effectiveness of the mitigation measures.

4.2.3.2. Crossing structures

- Depending on the climate and soil, plantings on wildlife overpasses and approaches to the structures may require watering for the first few years.
- Implement crossing structure maintenance programs, similar to structures built for other purposes.
- Pay specific attention to potential debris at structures with streams or rivers.
- Pay attention to large trees and shrubs on overpasses and make sure they do not threaten the integrity of the structure or that they could fall off the overpass on the road below.

5. SECTION B: LARGE DOMESTICATED SPECIES

5.1. Introduction

This section is organized by the following species groups:

- "Free roaming large livestock species": Cattle and horses that are domesticated, that have owners, and that are kept and raised in an agricultural setting for food, other animal products, or physical labor, but whose movements are not fully restricted and that have access to some highway sections because livestock fences along the right-of-way are either absent or not functional.
- Feral species": Horses ((*Equus ferus*), sometimes referred to as "mustangs" or "wild horses") and donkeys ((*Equus africanus asinus*), sometimes referred to as "wild donkeys" or "burros") that have escaped from captivity, that have been set free on purpose, or that are descendants from such individuals, and that now live similar to a wild animal species in North America.

5.2. Free Roaming Livestock

In many places in the western U.S. there are vast areas of open range on both public and private lands. In open range areas, livestock are not required to be contained and are free to move across the landscape, sometimes including roads. In some cases, it is appropriate to simply install ROW fencing to keep livestock from accessing the road corridor, while in other cases livestock may need to be able to move freely across the road to access resources such as forage and water on either side. In these cases, fencing must connect to suitable crossing structures. When designing mitigation measures for livestock it is imperative to also consider the other wildlife in the area. Measures aimed at reducing collisions with livestock should not come at the expense of wildlife. In some cases, concentrations of livestock-vehicle collisions may coincide with concentrations of wildlife-vehicle collisions, though this is often not the case (Creech et al. 2019). In locations where livestock- and wildlife-vehicle collisions occur in the same locations, the mitigation measures for large wildlife species (see Section A) can effectively reduce collisions and provide connectivity for both wild and domestic species.

Despite only representing a small proportion of all animal-vehicle collisions nationwide, collisions with livestock can be locally abundant. Some states experience higher rates of collisions with livestock than others and form 15% of the reported animal-vehicle collisions in California and 16% in Utah (Perrin & Disegni 2003; Huijser et al. 2008a). Collisions with livestock can account for a significant portion of all animal-vehicle collisions and the associated human safety risks in some rural areas (Creech et al. 2019). Rural roads with high design speed, high speed limits, and no artificial lighting present the highest risk for human fatalities associated with animal-vehicle collisions. Collisions with livestock such as cattle and horses are much more dangerous on a per collision basis than collisions with wildlife, as the most abundant wild large mammal species in crash and carcass databases are much smaller and lighter (e.g. deer (*Odocoileus* sp.) (Cramer & McGinty 2018; Creech et al. 2019). In Montana, livestock collisions are three times as likely to result in a human fatality than collisions with wild species, and 1.5 times more likely to result in an incapacitating human injury (Creech et al. 2019). Similarly, studies in Utah, Nevada, and Texas have also found that livestock collisions are more likely to result in human injury or death than the average collision with a wild species (Wildlife Quality Improvement Team 2005; Burton et al. 2014; Cramer & McGinty 2018, Wilkins et al. 2019).

5.2.1. Roadside Animal Detection Systems

Animal detection systems use electronic sensors installed along the roadside to detect large animals (e.g., deer size and larger) that approach the road. After the animal is detected, signs are activated to warn drivers (Huijser et al. 2015b). These signs are very specific in time and place. The effectiveness of animal detection systems is variable, but they appear to reduce wildlife-vehicle collisions with large mammals by 33-97% provided that the sensors detect the target species reliably (Huijser et al. 2021). In general, animal detection systems are more successful for large bodied species which could include livestock, though they have primarily been studied for large wild mammals such as deer, elk, and moose.

Specifics:

- Animal detection systems can reduce collisions with large mammal species, but they do not reduce the barrier effect of roads and traffic. Therefore, depending on the goals and objectives of the project, an animal detection system may or may not be appropriate.
- Follow a step-wise approach when considering the implementation of an animal detection system (Huijser et al. 2015b).
- Animal detection systems should only be considered on 2-lane roads (Cramer & McGinty 2018), perhaps with a traffic volume of a few thousand vehicles per day at a maximum (Huijser et al. 2015b).
- Consider combining the detection and warning system with advisory or mandatory reductions in speed limit (Huijser et al. 2015b; 2017a) (Figure 57).
- Animal detection systems should still be considered experimental, and implementation should be regarded as a high-risk project as many projects fail because of technological, management, financial, or maintenance issues (Huijser et al. 2015b; 2021).
- If implemented, animal detection systems should be located near livestock-vehicle collision hotspots or used as a fence-end treatment to reduce the probability of just moving the hotspot to the fence-end (see section below on barrier fencing for livestock).
- Note that the study that found that the inclusion of an animal-detection system resulted in a 97% reduction in collisions with large wild mammals used the animal-detection system as a fence-end treatment, not as a stand-alone mitigation measure (Gagnon et al. 2019).

Figure 57. Animal detection system at night with reduced advisory speed limit in association with a detection, Harderwijk, The Netherlands. Note that if there is no wildlife detected, the LED sign has no message at all (it is black).

5.2.2. Physical Barriers (Fencing)

- Livestock fencing along the right-of-way is the most common and effective method to reduce collisions with livestock if properly maintained. However, livestock fencing can be a substantial barrier to wildlife movement (Jakes et al. 2018). When constructing fencing to keep livestock off roads and reduce collisions with livestock, the wildlife species in the area must also be considered.
- Livestock fencing can be problematic for wildlife if it is too high to jump, too low to crawl under, have loose or broken wires, have wires spaced too close together, can snag a leaping animal, are hard for running animals or birds to see, or create an absolute barrier (Figure 58).
- To address wildlife needs, fencing installed for livestock should be designed "wildlife friendly." Wildlife friendly fencing guidelines are available (e.g. Paige 2015). In general, wildlife friendly fencing includes smooth (not barbed) top and bottom wires, a top wire that is no more than 40 inches high to allow adult large wild ungulates to jump over, and a bottom wire that is at least 16 inches (preferably 18 inches) above the ground to allow young wild ungulates and species who typically do not jump (e.g. pronghorn), to crawl under (Figure 59). The top two wires should be at least 12 inches apart to reduce the likelihood of wild ungulates like deer and elk getting their legs entangled when trying to jump over. To avoid collisions with fencing by wildlife, including birds, fence markers can be used to make the fence more visible and reduce the likelihood of wildlife colliding with the fencing (Figure 60).

Figure 58. An elk (*Cervus canadensis*) got its leg caught in the right-of-way or livestock fence and died, near Bannack, Montana, USA.

Figure 59. Wildlife friendly livestock fence with smooth top and bottom wires, Montana, USA.

Figure 60. Fence markers (white vinyl strips with or without reflective tape) to increase fence visibility and reduce sage grouse strikes, Montana, USA.

- Fencing should also include measures such as gates and/or cattle guards at access points (roads, driveways) to keep animals from entering the fenced road corridor at these locations. Special attention should also be paid to fence-ends, particularly in locations where the fencing is only along the right-of-way (such as in open range areas) and does not continue along property boundaries along access roads.
- Livestock fencing must be continuously maintained. Specifically, livestock fences should be inspected for their integrity and for possible locations where livestock may be able to gain access to the fenced road corridor (broken wires or posts, soil erosion causing too large of a gap between the ground and the bottom wire, vegetation encroachment on the fence, broken trees or branches on the fence, and sediment-filled cattle guards (Gagnon et al. 2022).
- Other gaps in livestock fences may occur when off-highway vehicles access bypass locked gates by cutting through the fence, (Gagnon et al. 2022).
- Schedule fence surveys and cattle guard surveys, annually at minimum, and time them to occur before peaks in livestock collision periods, which tend to occur primarily in the fall (Creech et al. 2019, Gagnon et al. 2022).
- Schedule surveys after heavy precipitation, storm events, or periods of heavy recreational use.
- Complete maintenance as soon as possible after issues are detected.

5.2.3. Virtual Fencing

Virtual fencing involves certain individual animals wearing GPS collars in conjunction with a virtual fence set by land managers. Auditory stimuli (often a series of loud beeps) emit from the collar when the animal approaches the virtual fence, and a benign shock is felt if the animal passes the fence limit. Benefits for livestock management include the ability to frequently and efficiently move livestock from one pasture to the next, reduce the need for traditional (physical) fencing, and define new within-pasture boundaries such as exclusion from riparian areas (Jachowski et al. 2013; Anderson et al. 2014). This technology could also be applied to keeping livestock from accessing roads in certain locations, but this has not been studied and should be considered experimental. On the other hand, one would need to handle all individual animals and fit them with collars. There are relatively high costs associated with handling, collaring, and programming, and there are likely technical problems as well as public aversion to shocking animals.

5.2.4. Physical Barriers (Fences) in Combination with Crossing Structures

- Underpasses and overpasses are effective connectivity tools for free roaming livestock, but they should typically be combined with livestock fences (see previous sections). Similar to crossing structures designed for large wild mammal species (see Section A), their location, spacing, and dimensions should be designed based on the biology and ecology of the target species, and the objectives of the owner of the animals.
- When using wildlife-friendly livestock fencing, underpasses for livestock can provide connectivity for livestock, without the risk of livestock-vehicle collisions. If the purpose of the fences is to keep large livestock species out of the fenced road corridor, but if the wildlife friendly design of the fence still allows large wild species to enter the road corridor, the crossing structures may only need to serve livestock. Nonetheless, it is still important to consider the needs of wildlife species in the area and whether they would benefit from reduced direct road mortality and crossing structures.
- Crossing structures, wildlife-friendly fencing, cattle guards and other tools should be placed in areas with high rates of livestock-vehicle collisions, and where livestock need to be able to access lands on either side of the road (Cramer & McGinty 2018).
- In locations where livestock-vehicle collision hotspots coincide with wildlife-vehicle collision hotspots, crossing structures and wildlife fencing may need to be considered, though this is not always and not typically the case (Creech et al. 2019).
- Similar to designing fencing to reduce collisions with other species (see Sections A and C), the entire hotspot for livestock-vehicle collisions should be fenced and the barrier should also cover an adjacent buffer zone to reduce the likelihood of fence-end runs.
- Fence-end and access road treatments should be implemented as part of the “package”.
- Structures should be large enough for livestock to readily use them (unassisted movement) or large enough for livestock to readily use them when urged by handlers (assisted movement) (see Huijser et al. 2021 for assisted vs. non-assisted movements). The design process would be similar to that for wild animal species; the structures have to take the behavioral characteristics of the target species into careful consideration. In general,

underpasses built specifically for livestock can be smaller than those for large wild ungulates, however, it is critical to evaluate the needs of the other wildlife in the area when designing structures; the barrier effect of the road and traffic should not be increased when mitigating for livestock.
- Avoid gaps between fences and crossing structures.

5.2.5. Access Points

- Similar to mitigation aimed at wild species, areas that are fenced for livestock will need cattle guards or gates at driveways, access roads, and other access points.
- Use cattle guards with round bars instead of flat bars or use a widely spaced grate material instead of bars. Some horses in Nevada have learned to walk on top of cattle guards with flat-topped bars, making these ineffective where this behavior has been learned (Cramer & McGinty 2018).
- Install and tie in fence along the edge of and within crossing guard pits to prevent livestock from making cross-jumps or traversing the ledges of the pit. Ensure that there is no access to pit ledges as these can be traversed and render the cattle guard ineffective.
- Gate designs that provide a space allowing livestock to pass under or over the gate should be replaced or mitigated to avoid passage and collisions at those locations. These include single-arm gate designs and equestrian gates. Gate dimensions should match physical characteristics of effective livestock fencing. (Gagnon et al. 2022).
- Fully tie in right-of-way or livestock fence to all gates.
- For gates continually left open by public in areas with wildlife exclusionary fencing or livestock right-of-way fencing, consider informative signage or enforcement presence to increase gate closing compliance (Gagnon et al. 2022). Alternatively, use gates that are self-closing (see examples in Section A).

5.2.6. Fence-Ends

- To mitigate fence-end runs, please consult section A on mitigation measures for large wild mammals.
- Animal detection systems can be used as a fence-end treatment and have been highly effective in some locations (Gagnon et al. 2019).

5.3. Feral Horses and Burros

Feral horse-vehicle and burro-vehicle collisions are a considerable and increasing problem in certain areas (Cramer & McGinty 2018; Gagnon et al. 2022) as feral horse and burro populations have been steadily increasing on western U.S. public rangelands (Scasta et al. 2018). Collisions with feral large mammals can be locally common, can be a substantial concern for human safety, and may require the consideration of measures to reduce these collisions (Creech et al. 2019). The literature on research and best practice management for feral large mammals is limited (Boyce et al. 2021), particularly relating to interactions with roads (Gagnon et al. 2022).

5.3.1. Culling

- The most effective collision mitigation method is reducing or removing feral large mammal populations (Gagnon et al. 2022). The degree in which animals are removed from the free roaming population influences the probability of collisions (Huijser et al. 2021). For feral large mammals, culling or eradication from an area is often the preferred action from the perspective of biological conservation. However, in the case of North American feral horses and burros, there is opposition to culling and eradication, some populations are legally protected, and effective population size management is often challenging or failing (Norris 2018; Scasta et al. 2018).
- The federal Wild Free-Roaming Horses and Burros Act of 1971 closely dictates the management and protocols of feral horses and burros, but the Public Rangelands Improvement Act of 1978 orders the federal government to maintain “appropriate management level population sizes”. This can be done through, for example, removal, or killing, but there are numerous limitations in place (Scasta et al. 2018).
- Overall, culling is challenging as a mitigation tool; competing ecological and human dimensions factors confound the management of feral horses and burros (Scasta et al. 2018).
- If culling is used as a collision reduction tool, determine areas with higher FHB collisions and focus removal efforts there. This could reduce vehicle collisions dramatically and reduce fence survey and maintenance workloads (Gagnon et al. 2022). Land management agencies such as BLM can help reduce collisions by managing horse and burro population levels to below the maximum herd management number (Gagnon et al. 2022).

5.3.2. Relocation

- Relocation results in a reduction of the local population size. The degree to which animals are removed from the free roaming population influences the probability of collisions (Huijser et al. 2021).
- Removal typically consists of capturing feral horses and burros and holding them in captivity until some of them may be adopted. This effectively transfers the feral animals “back” into captivity, and then they become “livestock”. However, adoption rates are lower than the rate at which the animals are captured and held in captivity (Scasta et al. 2018). Adoption facilities have reached maximum capacity and holding horses and burros for potential later adoption is expensive and a burden on federal financial resources (Hendrickson 2018).

- Facilitate feral horse and burro adoption programs where possible. Explore opportunities to increase adoption rates. Increase program exposure through internal and external publications, use signage to increase awareness of collision issues and adoption opportunities, and/or incorporate collision information and links to adoption programs on state Department of Transportation websites (Gagnon et al. 2022).

5.3.3. Anti-Fertility Treatment

- Anti-fertility treatment can result in population reduction but may need to be combined with other measures. The degree to which the population is reduced influences the probability of collisions (Huijser et al. 2021).
- Anti-fertility drugs are applied to feral horses and burros when captured. Females are treated with birth control drugs and released. For these efforts to be successful, they must be administered regularly over long periods of time (Danvir 2018). Fertility control can slow population growth, but it has not reduced or stabilized populations as a standalone population control method in large populations (Garrott 2018; Grams et al. 2022). No single fertility-control method is highly effective, easily deliverable, long-term, and affordable to administer at this time (Danvir 2018; Hendrickson 2018). Anti-fertility treatments may need to be combined with other measures, and the treatments would benefit from improvements.
- Castration or gelding of male horses or burros is also an option. However, a high proportion of adult males need to be gelded for any long-term population reduction (King et al. 2022).
- For a collision mitigation tool, anti-fertility treatment or fertility control method does not result in an immediate reduction in population size (Garrott 2018), and therefore a reduction in collisions is not expected, at least not on short term.

5.3.4. Roadside Animal Detection System

- See the section on animal detection systems for livestock.

5.3.5. Virtual Fencing

- See the section on animal detection systems for livestock.
- Virtual fencing would require individual animals to carry GPS collars. This would likely affect how people perceive the feral horses and burros; they would no longer seem “wild and free” but more like livestock. In addition, feral horses and burros would be shocked when they approach a virtual fence. This may also receive critique.
- Capture and handle effort would be high and continuous as the batteries would need to be replaced regularly.

5.3.6. Physical Fences

- If culling or relocation of feral horses and burros is not an option, fencing is the most effective measure to reduce collisions. Standard right-of-way fences are typically a barrier for large livestock species such as cattle, horses, and burros, whether domestic or feral.

Research in Arizona found that burros did not cross over wildlife fence or intact 42-inch-tall right-of-way fence (Gagnon et al. 2022). Upgrading and maintaining right-of-way fences is generally the most straight forward strategy to keep feral horses and burros off highways.

- It is possible that feral horses may cross over 42-inch-tall right-of-way fences; in areas with feral horse collision concerns, taller fences may be required.
- Make feral horse and burro fences wildlife-friendly (see Paige 2015). The bottom wire should be 18 inches above ground level, but not higher. Burros cannot pass beneath fences with bottom wire heights at or lower than 18 inches above ground level (Gagnon et al. 2022) and presumably, this is the same for horses.
- Mitigate locations where fence sections include bottom fence heights higher than 18 inches. These often occur at locations where topography changes dramatically over short distances, such as where right-of-way fences enter steep-sided washes (Gagnon et al. 2022). Gagnon et al. (2022) recommend the following options, used separately or in combination:
    - Install a deadweight hang (a heavy object attached to the fence) intended to pull the fence closer to ground level and anchor fence posts.
    - Install additional wires beneath the standard four strands.
    - Span the gap with a single fence span and hang material from the bottom wire and cut to length beneath the fence.
    - Shorten fence spans that traverse steep topography, so the fence posts are installed and anchored as close to the top and toe of a slope as possible and wire hung between the posts runs parallel to the ground.
- While right-of-way fencing is required to keep feral horses and burros off highways, right-of-way and/or livestock fences can have unintended negative side effects for wildlife species. These effects include potential death and injuries, and the fence acting as a barrier (Jakes et al. 2018; Jones et al. 2020). Livestock fence designs that are less dangerous and more permeable to large wild ungulates exist and can be considered in areas where large wild mammals are also present. Wildlife-friendly livestock fences typically have smooth wires on the top and bottom, a top wire no higher than 42 inches, and a bottom wire between 16–18 inches from the ground (Paige 2015). Since burros pass under fences higher than 18 inches, the lowest wire needs to be no higher than that height in areas with burros. Between Clark and Silver Springs, Nevada, a 4-strand fence was constructed to keep feral horses of the highway while offering wildlife-friendly components including smooth and bottom wires, with two middle barbed wires) (personal comment Nova Simpson NVDOT).
- Where Jersey barriers function as right-of-way fence, top or back the barriers with barbed wire or chain-link fence to discourage feral horses and burros from climbing or jumping over the barrier.
- If only one side of the right-of-way is fenced, install fencing along the unfenced side of the right-of-way as well.
- Rather than right-of-way fence, a taller, more robust wildlife fence can be erected that would keep both feral species and wild large mammal species off the road. However, this would then also mean that suitable wildlife crossing structures are included for both wild species, and potentially also for feral horses and burros.

- Fencing and associated measures such as gates and cattle guards must be continually maintained (Gagnon et al. 2022).
- Schedule fence surveys and cattle guard surveys, annually at minimum, and time them to occur before peaks in collisions with feral horses and burros, which tend to occur in the fall (Creech et al. 2019; Gagnon et al. 2022).
- Schedule surveys after heavy precipitation, storm events, or periods of heavy recreational use.
- Complete maintenance as soon as possible after issues are detected.

5.3.7. Barriers (Fences) in Combination with Crossing Structures

- Underpasses and overpasses for feral horses and burros would be similar to those designed for large wild mammal species. Their location, spacing, and dimensions should be designed based on the biology and ecology of the target species, especially because their movements would be unassisted (in contrast to some livestock movements) (see Huijser et al. 2021).
- Crossing structures, fencing, and cattle guards and other measures should be placed in areas where feral horses and burros are involved in collisions and/or in areas where connectivity is desired (Cramer & McGinty 2018; Huijser et al. 2021).
- Crossing structures and fencing should be added particularly if a location coincides with collision hotspots of both feral animals and wildlife, though typically they are not at the same location (Creech et al. 2019).
- Burros readily used below-grade drainage structures (Gagnon et al. 2022) and wildlife underpasses (Bristow & Crabb 2008).
- Feral horses do use underpasses. Two underpasses for feral horses were constructed between Clark and Silver Springs, Nevada (Xu & Tian 2019). These large box culverts (20 ft (6.1 m) wide, 13 ft (4 m) high, across 4 lanes with a median) were used by feral horses after they were “baited” with water in a water tank.
- If wildlife crossing structures are intended for wildlife movement but if the passage of feral horses or burros is not desirable, consider wildlife-friendly livestock fencing at the entrances of the structure (Gagnon et al. 2022).
- Avoid gaps exceeding 6 inches between fences and crossing structures.

5.3.8. Access Points

- In areas with fences for feral horses and burros, install cattle guards at access roads and driveways. Single cattle guards with a width of 8 feet effectively prevent burros from accessing the right-of-way, particularly when cattle guard vaults are clear of sediment (Gagnon et al. 2022).
- Use round bars instead of flat bars or use a grate material instead of bars. Some wild and feral horses in Nevada have learned to walk on top of cattle guards with flat-topped bars, making these ineffective where this behavior has been learned (Cramer & McGinty 2018).
- Install and tie in fence along the edge of and within cattle guard pits to prevent feral horses and burros from accessing the right-of-way using the ledges. Additionally, add

angle iron along the pit ledge or use rubber bumpers to reduce access to the pit ledge (Gagnon et al. 2022).

- Gates should not have gaps that potentially allow feral horses or burros to enter the right-of-way. Gate dimensions should match physical characteristics of effective right-of-way fencing. Openings greater than 18 inches in height should be blocked (Gagnon et al. 2022).
- Fully tie in right-of-way fence to a gate.
- For gates that are repeatedly left open in areas frequented by the public, consider informative signage or enforcement (Gagnon et al. 2022).

5.3.9. Fence-Ends

- To mitigate fence-end runs, review section A for wild large mammals.

6. SECTION C: SMALL WILDLIFE SPECIES

6.1. Introduction

This section relates to small terrestrial wildlife species. This includes small wild mammal species (no minimum size for the species, but maximum size is similar to a coyote), wild reptile species, and wild amphibian species in North America that are fully or predominantly terrestrial. This excludes flying species and arboreal species. Note that invertebrates are also excluded.

6.2. Planning and Design of Wildlife Fences or Other Barriers

- As a general rule, barriers for small wild animal species should be combined with crossing structures; these measures should be regarded as a package. For high volume roads and roads that cannot be closed or removed, the combination of barriers and crossing structures is the most robust and effective way to reduce direct road mortality for small animal species while also allowing the animals to cross to the other side of a road. Note that while crossing structures as a stand-alone measure can provide connectivity, they need to be combined with fences or other barriers to reduce direct road mortality.
- The importance of the planning process cannot be overstated. What is or what are the problems? The target species? The road sections that are of concern? Buffers zones? Barriers are often too short in length; many do not cover the full length of a roadkill hotspot, let alone an adjacent buffer zone. This means that animals still access the road at or just beyond the fence-ends (Gunson & Huijser 2019f). Likely the best approach is to mitigate the entire road length (and associated buffer zones) that bisects suitable habitat for a species, regardless of where current concentration of direct road mortality may be located (Langton & Clevenger 2020). Many mitigation measures are not implemented at a sufficiently large spatial scale (Huijser & Begley 2022). In some cases, the habitat may be homogeneous and extensive and occur for more than several miles alongside a road. If barriers cannot extend along the entire habitat for practical or monetary reasons, they should at least extend the full length of known roadkill hotspots, animal crossing areas, and adjacent buffer zones.
- Barriers for small animal species tend to be, on average, less effective than those for large mammal species. This is likely because it is harder to design effective barriers for species that are small or species that are good at climbing or digging. A review of the effectiveness of barriers in reducing direct road mortality of small animal species found an average reduction of 65% (minimum 16%, maximum 100%) (Gunson & Huijser 2019). It is possible to design barriers for small animal species that would be 80-100% effective in reducing direct road mortality. However, this requires more effort during the design and installation (Huijser et al. 2021).
- A permanent barrier fence or guide wall may be more easily installed along roads that are newly constructed or reconstructed, e.g., twinning expansions and widenings when the road surface and roadbed are reconstructed for transportation needs already (Gunson & Huijser 2019c).
- Guide walls are a specific form of barrier. They differ from fences as they present an open face in one direction, similar to a retaining wall, and they are flush to the ground

surface on the other side (Figures 61-62). These are “one way” barriers and allow animals that do get into the roadway to easily return to the safe side of the barrier at any location. When designed and constructed appropriately, guiding walls require less maintenance effort over time than fences as fences are more easily damaged by mowing or falling trees and in some cases erosion (Jackson et al. 2015; Gunson & Huijser 2019c; Langton & Clevenger 2020).

Figure 61. A “fence” designed for Eurasian badger (*Meles meles*) (the taller metal fence material with small mesh size) and for common toad (*Bufo bufo*) (the plastic sheets at the bottom of the fence), Rijksstraatweg Elsterstraatweg N225 just west of Elst, Utrecht, The Netherlands.

Figure 62. A "barrier wall" (polymer concrete) for common toads (*Bufo bufo*), integrated into roadbed, Deelenseweg, between Hoenderloo and Arnhem, Gelderland, The Netherlands.

- More detailed specifications include the height, the fence material, post specifications, and mesh size (Figures 63-67). Fence design should be based on the behavior and agility of the target species. Considerations include the ability for an animal to move, jump, swim, climb, dig, and exercise force against the barrier. As a general rule, for small animal species, Smith et al. (2015) note that fencing should be at least 90 cm (3 ft) above ground and 30 cm (1 ft) below ground. This may vary depending on the target species (see below for more specifics based on species and size).

Figure 63. Wildlife fence for Eurasian badger (*Meles meles*) and wild boar (*Sus scrofa*), N302, Leuvenumseweg, Sonnevanck, east of Harderwijk, The Netherlands.

Figure 64. A chain-link turtle fence continues above a culvert for turtles, Valentine National Wildlife Refuge, Nebraska, USA.

Figure 65. Barrier wall for turtles, alligators, snakes and amphibians, Lake Jackson Ecopassage, Tallahassee, Florida, USA. The barrier wall was under construction when the image was made.

Figure 66. A "barrier wall" (concrete) integrated into the roadbed for common toads (*Bufo bufo*), Deelenseweg, between Hoenderloo and Arnhem, Gelderland, The Netherlands.

Figure 67. Fence to keep desert tortoise (*Gopherus agassizii*) off the highway, California, USA.

- If there are multiple target species, ranging from large wild mammals to amphibians, different fence materials can be integrated into one barrier design (Figures 68-69).

Figure 68. Mesh wire wildlife fence with metal poles on top of multifunctional overpass (wildlife, bicyclists, pedestrians; about 100 m wide), across A4 motorway, Parndorf, Austria. The overpass is designed for farmers, agricultural machinery, hunters and wildlife including roe deer (*Capreolus capreolus*) and European hare (*Lepus europaeus*). Mesh size is small towards the bottom.

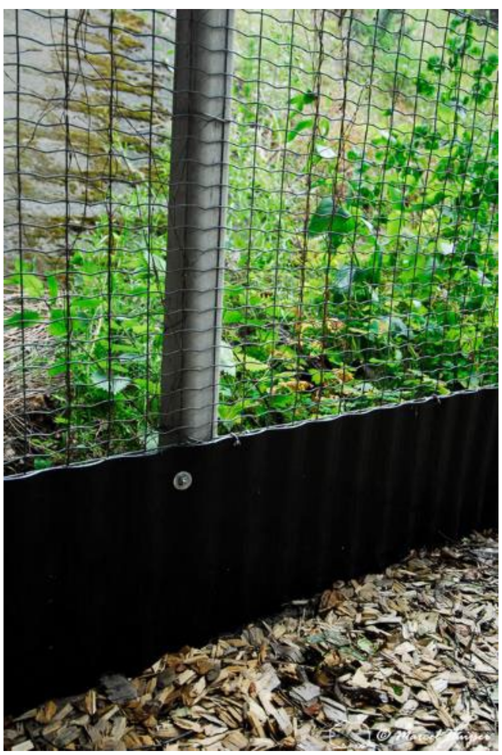

Figure 69. Wildlife fence for Eurasian badger (*Meles meles*) (mesh wire) and common toad (*Bufo bufo*) (ABS sheets), The Netherlands.

- Fences should typically be buried to deter animals from digging under the barriers (Figures 70-71). Buried fencing recommendations range from 5 cm to 30 cm (Huijser et al. 2008c; Smith & Noss 2011), and a 20 cm wide flat platform at the base of a guide wall is recommended to deter vegetation growth which may allow small animal species to climb over the barrier (SETRA 2005; Jackson et al. 2015).

Figure 70. Wildlife fence and dig barrier (or "apron"), mostly for canids and bears (*Ursus* sp.), Trans-Canada Highway, Banff National Park, Alberta, Canada. The dig barrier angles away from the road and keeps the animals from digging under the fence.

Figure 71. If a dig barrier cannot be dug into the soil, angling it away from the road and covering it with soil and rocks and boulders may be an option. Trans-Canada Highway, Banff National Park, Alberta, Canada.

- Fences sometimes require an overhang or top lip to deter animals from climbing over the barriers (Figure 72-74). Fences for small animals typically have an overhang (4–6 cm (2–3 in)) at a 45–90º or greater angle away (Huijser et al. 2008c).

Figure 72. Barrier wall integrated into the roadbed with overhang for reptiles, amphibians and small mammals, U.S. 441, Paynes Prairie Ecopassage, south of Gainesville, Florida, USA.

Figure 73. Fence with overhang for American crocodile (*Crocodylus acutus*), Key Largo, Florida, USA.

Figure 74. Fence designed to keep koala (*Phascolarctos cinereus*) off the highway, M79, between Harcourt and Faraday, Victoria, Australia. This fence is about 2.1 m high, and the top 50 cm or so angles away from the road. The last 30 cm or so is not supported by the post and forms a 'floppy top' making it difficult to cross by species that climb well.

- Barriers are most likely to be effective at locations where target species predictably cross in the same location every year. Prioritize the installation of barriers along road sections that have shown a consistent mortality problem over many years to minimize the risk of mitigating the wrong road sections (Gunson & Huijser 2019f).
- The known daily (or nightly) movement distances (or home range) of the target species can inform decisions about the minim functional barrier length along roads as well as the appropriate spacing of crossing structures (Gunson & Huijser 2019c; Langton & Clevenger 2020).
- Partial barriers (i.e., barrier on one side of the road or with gaps) are typically not effective. Implement barriers on both sides of a road and start and end the barriers at the same location on opposite sides of the road when suitable habitat or terrain exists (i.e., no staggered fence ends). Mitigate gaps at access roads or driveways (Gunson & Huijser 2019f) (Figure 75).

Figure 75. ABS plastic sheets to keep common toads off the highway (highway is to the left of the image), and an amphibian tunnel under an access road. Amphibians that approach the access road would fall in between the bars. Amphibians that travel along the barrier would go through the tunnel, continue to travel along the barrier on the other side of the access road until they encounter a tunnel that allows them to cross to the other side of the highway.

- Height of fencing should consider the potential of vegetation or debris to build up against it, which may allow small animals to crawl over the fence (Dodd et al. 2004; Langton & Clevenger 2020). This may result in higher fences than what would be required based on the jumping or climbing abilities of the target species alone.

- The main types of permanent barrier materials for small animals are wood, plastic, concrete, metal sheeting, chain-link, and hardware cloth. Chain-link or woven wire are common fence materials, and chain-link and plastic sheets were deemed the most effective in some studies (Gunson & Huijser 2019c; Langton & Clevenger 2020).
- The life span of barriers varies with materials used, site conditions, installation procedures, and frequency or extent of maintenance. Smith et al. (2015) and Langton and Clevenger (2020) examine pros and cons of different fencing materials for small animals.
- Mesh size and wire thickness ('gauge') are considerations for metal fencing. Typically, wire fencing used for large animals has mesh sizes that are too large for small animal species, and they may move freely through the fencing and onto the roadway.
- Mesh wire fences may be appropriate though for medium sized mammals, and large reptiles (e.g. most turtle species). Mesh wire is available in different gauges. Thick wire (e.g. 2.5 mm diameter (American Wire Gauge 10) or thicker) is more durable than thin wire and results in a greater life span (Kruidering et al. 2005; Clevenger & Huijser 2011). Most woven wire mesh fencing is galvanized with the highest degree of protection resulting in a life span of at least 15-20 years (Clevenger & Huijser 2011).
- According to Smith et al. (2015), metal mesh (0.25 inch, hot-dipped, galvanized metal mesh of at least 23-gauge and with at least 29% weight in zinc) is the most cost-effective fencing for small animal species, while aluminum flashing is the most effective biologically but can be cost prohibitive and can cause drainage issues as it can block water flow.
- Hardware mesh cloth is commonly used and allows drainage, but it is not recommended as a "stand alone" installation because the fence is subject to trampling, and the material is exceptionally sharp and dangerous for animals when displaced. Applications of hardware cloth with a sturdy wood or metal framework have been successfully installed in Ontario, Canada, and have lasted up to six years (Gunson & Huijser 2019c).
- To direct small animals toward the entrance of a passage structure, a septum fence or barrier, also called a passage entrance deflector board can be placed at the entrance of the structure to reduce the likelihood that animals bypass it (Jackson et al. 2015; Langton & Clevenger 2020).
- On overpasses, an opaque barrier should be included to prevent small and medium-sized species from falling off the overpass.
- Maintenance of fences or other barrier structures is critical to their effectiveness in reducing direct road mortality (Baxter-Gilbert et al. 2015; Reses et al. 2015).

6.3. Barrier Considerations for Mammal Species

- For medium-sized mammals, fences should be substantially longer than 100 m (on both sides of a passage), as 100 m was insufficient for avoiding increased amounts of fence-end mortality (Plante et al. 2019). Fence length should be determined by locations of collisions or suitable habitat, and associated buffer zones based on the mobility of the target species.
- Fencing for medium-sized mammals is typically 0.9-1.8 m (3-6 ft) high; a 1.15 m (4 ft) high fencing combined with a 60 cm (2 ft) curved 'floppy' overhang is also effective (Huijser et al. 2015a).

- Oftentimes smaller meshes (8 cm (3 inches)) are used at the bottom of a large mammal fence to also exclude medium sized mammals (Kruidering et al. 2005; Clevenger & Huijser 2011). For small mammals, fine mesh sizes (1 x 1 cm (0.5 x 0.5 in)) may be used at the bottom of the fence, usually as separate fencing material that is tied into the main large mammal fence.
- Some fencing designs have included electrical fencing for medium-sized animals along the bottom (about 9 cm (3.5 inches) above the ground) and at the top to prevent animals from digging under or climbing over (Huijser et al. 2015a) (Figure 76).

Figure 76. Wildlife fence along A28 motorway, near Spier, Drenthe, The Netherlands. The fence is a barrier for medium and large mammal species. The electrified wire is an additional barrier to keep animals from climbing the fence.

- Conan et al (2022) found wire netting fence ineffective, particularly for agile rodent species such as hamsters and voles. In Western Europe, wire netting fence between 30 and 60 cm high (with a typical mesh size of 6.5×6.5 mm) is, despite research showing its ineffectiveness, commonly used for small vertebrate species and is attached to the large-fauna fences (2022). Hamsters and voles could easily climb the fencing, even when including a slight (10 cm (and voles, up to 15 cm) overhang. It is recommended that overhangs must be included and should be longer and made of solid/non-climbable material such as metal plating. More effective, durable, and less climbable fence materials than wire netting fence are also recommended for small mammals.

6.4. Barrier Considerations for Reptile and Amphibian Species

- Minimum barrier height varies based on the target species. Some species will also require an overhang and dig barrier to stop the animals from being able to cross over or under the barrier. Minimum barrier heights can range from only 13 inches (7.6 cm) for some small lizards to 60 inches (152 cm) for large snakes (snakes are less likely to cross over a fence if it is at least as high as the snake is long). Overhangs on barriers are needed for lizards, snakes, salamanders, newts, toads, and frogs, but may not be needed for turtles and tortoises so long as the barrier material cannot be climbed. Due to the behavioral characteristics of different species in terms of climbing, jumping, and digging it is helpful to consult with specialists that have specific knowledge of the species to determine the best material to prevent fencing breaches (Huijser et al. 2021; Langton & Clevenger 2020).
- Barrier material and solid versus open mesh construction is crucial to consider when designing for reptiles and amphibians. Species that rely heavily on visual and olfactory cues will often spend more time investigating and trying to breach non-solid barriers. Brehme and Fisher (2021) found that California tiger salamanders moved an average of nearly twice as fast along solid barriers as they did along open mesh fence and they were 3 times less likely to turn around and pace the fence when solid. Open mesh fencing is also easier to climb, and some species may become trapped in the mesh if trying to push through. Where open-mesh fencing is already installed, it can be retrofitted by adding a visual barrier at ground level to the existing fencing (Milburn-Rodríguez et al. 2016; Langton & Clevenger 2020; Brehme & Fisher 2021)
- Chelonid species such as turtles and tortoises are more likely to walk along barriers that they can see through and more likely to move away from solid barriers, so this is an important distinction for these species if the fencing is meant to guide the animals to a safe crossing opportunity (Figure 77). These species may dehydrate and die from heat exhaustion in some cases if they do not find shade or cover and may require shade structures to be provided at appropriate intervals based on movement speeds (Langen 2011; Peaden et al. 2017; Boyle et al. 2019; Langton & Clevenger 2020).

Figure 77. Common snapping turtles (*Chelydra serpentina*) have been walking along a chain-link turtle fence, both on the road side and safe side, Valentine National Wildlife Refuge, Nebraska, USA (Huijser et al. 2017b). One turtle is visible on the roadside (right) of the fence.

- Particular habitat types, landscapes, and climate considerations may make different materials better suited for precipitation, wind, and soil and water erosion. Landscape aesthetics may also be important. Solid barriers including guide walls tend to be more expensive, but also more durable, as long as soil and water erosion processes are not too extreme. Barrier longevity will be influenced by temperature, light and moisture patterns, and vegetation/landscape attributes (Langton & Clevenger 2020).
- Mesh fencing allows the movement of air, water, and soils to pass through and may be the most suitable material in harsh environments with high winds and/or poor soil drainage and associated in sheet flow runoff.
- Fence-end treatments are critical for reptile and amphibian species (see section on fence-ends below).
- Barrier angle in relation to the road and the crossing structures is an important consideration for reptiles and amphibians, especially migrating adults who may turn back and not breed if barriers are not constructed at the correct angles to guide them to a crossing location, or if they are not able to reach a safe crossing opportunity within their active movement period. Where crossing structures are provided very frequently (60 feet or less spacing between structures), the barriers can be installed parallel to the road. However, if the structures are provided less frequently, the barrier needs to be installed at a suitable angle moving toward the crossing location to guide animals to the structure (Langton & Clevenger 2020; specs provided on p.65 of that document).
- Passage entrance deflector boards, short sections of barrier that keep animals from walking past the structure and direct their movement into the structure are also an important detail. These may be made of wood or other materials and should extend into

the structure slightly, but not block animal movements out of the structure (Langton & Clevenger 2020).

- Fence effectiveness is reduced and road mortality can occur at gaps in barriers at intersections, access roads, driveways, etc. Consider effective treatments such as passages or grates and barriers at these gaps to reduce animal breach locations (Langton & Clevenger 2020).

6.5. Planning and Design of Wildlife Crossing Structures

- Mitigation measures aimed at reducing collisions with small animal species such as small mammals are partially similar to those for large wild mammals. While some crossing structures include small mammals among the target species and while they are designed to meet their specific habitat requirements, many overpasses and underpasses are primarily constructed for large mammals and happen to also accommodate small animal species.
- The distance between large structures for larger wildlife is typically much larger than the home range of small animal species; smaller suitable structures are typically required at much shorter intervals (e.g., ten or several dozens of meters up to perhaps hundreds of meters depending on the species) (Bissonette & Adair 2008; Ottburg & van der Grift 2019; Brehme et al. 2021). Spacing intervals of structures should be a function of home range size and dispersal capabilities of the target species, and those movement distances can be quite short for many small animals (Grilo et al. 2018, Matos et al. 2019). Therefore, the location of a crossing structure and the spacing between them are among the most important factors that influence passage success and the level of connectivity that the crossing structures provide (Jackson et al. 2015; Langton & Clevenger 2020).
- Designated structures for small animals should be located where improved connectivity for target species would have the greatest benefit for survival of the population (Clevenger & Huijser 2011). Understanding the biology and motivations for movement of the target species is essential for locating structures (Jackson et al. 2015; Langton & Clevenger 2020).
- There are usually fewer data on small animals than large animals, so planners must use a variety of sources of data and natural resource agencies should be prepared to maintain and share species occurrence data with transportation agencies (Langen et al. 2015).
- If crossing structures are not used by the target species, the road can become an absolute barrier. When crossing structures are not adequately spaced or there are not enough structures to match the movement distances of the target species, animals will either turn back or find a way to cross at-grade. While the impacts of roads on small mammal species may not appear problematic because their population densities are generally high, this is not always the case (Conan et al. 2022). For instance, some European species are endangered and declining at an alarming rate, such as the garden dormouse (*Eliomys quercinus*) and the European hamster (*Cricetus cricetus*) and roadkill is important to address (Conan et al. 2022). Well intended mitigation of barriers and crossing structures, can also lead to a population crash for amphibians such as the common toad (*Bufo bufo*) if the number of crossing structures is insufficient and keeps a sizeable portion of the

population from moving between winter and breeding habitat (Ottburg & van der Grift 2019).

- Typically for small animals, more wildlife crossing structures are better than fewer. Some guidelines include a general rule of one passage every 300 m, though this minimum sometimes must be exceeded with passages every 10-30 m (i.e., for amphibians) (SETRA 2005; Brehme et al. 2021; Langton & Clevenger 2021). A density of >1.0 small culvert per km was found to allow small mammal movement in one study (Hennessey et al. 2018).
- If there are multiple target species with different habitat requirements, multiple structures that accommodate different species requirements may be required (Table 4). Alternatively, larger structures that accommodate various habitat types and environmental conditions can help address this issue (Mata et al. 2005; Jackson et al. 2015; Hennessey et al. 2018) (Figure 78-79).

Figure 78. Cover, grassland, and edge habitat on top of multifunctional overpass (wildlife and farm road, about 100 m wide), across A4 motorway, Parndorf, Austria. The overpass is designed for farmers, agricultural machinery, hunters and wildlife including roe deer (*Capreolus capreolus*) and European hare (*Lepus europaeus*).

Table 4. Suitability of different types of mitigation measures for selected small and medium-sized mammal species (for 2-3 lane highways [25-35 m (82-115 ft)] wide road without median).
1 Recommended/Optimum solution; 2 Possible if adapted to species' specific needs; 3 Not recommended; 4 Unknown, more data required (Clevenger & Huijser 2011, O'Brien et al. 2013, Ford et al. 2017, Huijser et al., preliminary data; Clevenger, unpublished data).

	Wildlife overpass	Open span bridge	Large mammal underpass	Medium mammal underpass	Small-medium mammal pipes
Badger	1	1	1	1	1
Beaver	2	1	1	4	4
Fisher	1	1	2	2	2
Grey fox	1	1	1	1	1
Opossum	1	1	1	1	1
Porcupine	1	1	1	4	3
Raccoon	1	1	1	1	4
Red fox	1	1	1	1	1
Ringtail	1	1	1	2	2
Skunks	1	1	1	1	4
Squirrels	1	1	1	3	3
Wolverine	1	1	4	4	3

Figure 79. Wildlife underpass and fence with grasses, shrubs, and trees in the median and also some under the bridges, US Hwy 64, near Roper, North Carolina, USA.

- Topographic features like draws, valley bottoms, and ridges, and habitat edges are often where wildlife are channeled. When habitat is continuous or without topographic features, animals may have no apparent areas of concentration; directional fences or guide walls leading to multiple structures are highly important. If there is evidence of certain areas having high movement, clusters of small structures may be useful (Jackson et al. 2015; Langton & Clevenger 2020).
- Structures vary in shape from round, elliptical, arched, or box and are made of materials that range from metals (e.g., corrugated steel pipe), plastics (e.g., high-density polyethylene), polyvinyl chloride, or cement. Use of polyethylene as a construction material for culverts was negatively correlated with wildlife use in one study (Brunen et al. 2020).
- Maintain natural substrate on the bottom (Figure 80). This is more likely to match nearby natural conditions (soil, soil and air temperature and humidity). Design features should mimic conditions in the surrounding environment.

Figure 80. Corrugated metal culvert with soil covering the bottom.

- Open-bottom structures like arched culverts on footings or three-sided culverts allow for natural substrate and moisture conditions to be more similar to the surroundings (Gunson & Huijser 2019b) (Figure 81).

Figure 81. Bottomless culvert.

- When structures have a solid floor (i.e., are a round tube) rather than an open bottom, it is preferable to be placed below grade and filled with natural substrate to match the adjacent ground level (Jackson et al. 2015; Brehme & Fisher 2021; Langton & Clevenger 2020) (Figure 82).

Figure 82. Corrugated metal culvert with bottom placed below the ground level of the surroundings, US Hwy 93, near Ravalli, Flathead Indian Reservation, Montana, USA.

- Data on specific sizing for crossing structure are not available for most species of small and mid-sized mammals; a focal or target species is often used as a representative for an area of species, or a structure is made large enough for many smaller species. In theory, wider tunnels work better for smaller animals that move short distances because they are more likely to find the entrance when migrating across the landscape (Gunson & Huijser 2019b).
- Some sizing generalities can be made: an analysis of research articles found that box culverts are on average 2.4 m wide by 1.8 m high and have been installed and shown use by amphibians, reptiles, and small mammals (Gunson & Huijser 2019d). Small-sized underpasses (1–1.5 m wide) are also used by small- to medium-sized species, such as marten, coyote and bobcat (Cain et al. 2003; Ng et al. 2004; Grilo et al. 2008). Further guidelines can be found in Clevenger and Huijser (2011) and Langton and Clevenger (2020) (Figures 83-84).
- In general, overpasses tend to be well suited for small animal species, since overpasses are typically large enough to host a variety of habitat types and micro-climates (McGregor et al. 2015).

Figure 83. Culvert for long-toed salamander (*Ambystoma macrodactylum*), Waterton Lakes National Park, Alberta, Canada.

Figure 84. Wildlife underpass, Nuevo Xcan-Playa Del Carmen highway, Quintana Roo, Mexico.

- Since it may take considerable time to cross the length of a crossing structure, it is important that small animals find everything they need on top of or inside a crossing structure, including continuous suitable habitat or steppingstones of suitable habitat with relevant amounts or types of cover, food, and water, as well as light, temperature, and soil (McGregor et al. 2015) (Figures 85-86).

Figure 85. Wildlife underpass with branches along the side for cover for small mammals, Montana, USA.

Figure 86. Root wads leading up to and on top of wildlife overpass as cover for small animal species, The Netherlands.

- Underpasses usually have limited light and precipitation, and this severely reduces vegetation, cover, and food inside many underpasses. To be made more suitable for small animals, over-size the structure to maximize light, moisture and air at the entrance of the structure (Figure 87) and allow for multiple design features such as shelving for multiple species and animal groups.

Figure 87. Tall bridges allow for light and moisture under the structure, and for continuous habitat for nearly all species, including small animal species, China.

- Keep structure length to a minimum (Jackson et al. 2015; Chen et al. 2021); small mammals are more likely to use shorter passages (McDonald & Cassady St. Clair 2004). To address this, consider increasing the width and/or height of a structure for wider roads (Gunson & Huijser 2019f)
- Water may be available in some underpasses if the underpass is combined with a stream or river crossing, or where it crosses a wetland. A stream or river crossing should preferably have natural stream dynamics and natural substrate so that the hydrological conditions are similar to those outside the structure. For rivers and streams, bottomless structures are recommended. This allows for natural substrate and stream dynamics.
- At the area approaching the crossing structure, ensure there is sufficient cover and that the approach matches that of the surroundings (Figure 88-89). Available cover and natural characteristics in the approach areas to crossing structures is important for small and mid-size mammals (Clevenger & Waltho 1999; Ascensao & Mira 2007; Grilo et al. 2008). Riparian and terrestrial habitat at entrances further increases the use by species that

depend on those habitat types. However, vegetation that is too dense and obscures the visual opening or prevents small mammal passage of a culvert should be selectively removed or thinned (Smith et al. 2015).

Figure 88. Cover close to the entrance of an amphibian tunnel, The Netherlands.

Figure 89. Vegetation providing cover at the approach of a wildlife underpass, US Hwy 95, Bonners Ferry, Idaho, USA.

- Cover is highly important for small mammals and some reptile and amphibian species; small and confined structures may be used more readily by certain small mammal species than larger structures that have no or limited cover (Foresman 2004; McDonald & Cassady St. Clair 2004; Hennessey 2018; Brehmen et al. 2021). Incorporating elements that match the natural habitat into underpasses is also important for mid-size mammals (Grilo et al. 2008).

- Provide cover for resting or hiding within both underpasses or overpasses, using natural materials such as branches, logs, root wads, and rocks or artificial materials including concrete cinder blocks or PVC pipes (D'Amico et al. 2015). Shrubs, grasses, and other understory vegetation also provide important cover (Millward et al. 2020). Tubes or pipes can be placed within a larger structure to assist species that prefer small, confined spaces like weasels and other small mammals (Clevenger & Waltho 1999; Foresman 2004) (Figures 90-91). These can be integrated into the walkway design or attached to the walkway to encourage small mammals (mice, voles) to use the walkway.

Figure 90. PVC pipe as artificial cover in an underpass, Montana, USA.

Figure 91. Boulders provide cover to small animal species and block access to unauthorized vehicles at wildlife underpass, US Hwy 95, Chilco, Idaho, USA.

- Wildlife passages should be designed and managed to exclude stormwater and areas where flooding may occur, as most small mammals are deterred by flooding or standing water (Jackson et al. 2015). Barriers are often compromised with high water levels and wash-outs from groundwater flow, especially when barriers are near the road pavement surface. Consider effective placement of barriers, selection of materials, and installation methods to reduce water flow impacts (Gunson & Huijser 2019f).
- When this is not possible and when drainage culverts or underpasses are frequently flooded but not fully submerged, adequately sized ledges, shelves, or rails placed above high-water levels are recommended to facilitate drier passage for terrestrial animals (Goldingay et al. 2018; Brehme & Fisher 2021) (Figure 92). Concrete, wood, or grate shelving are successfully used for small and mid-sized mammals like mice, voles, bobcats, skunks, weasels, and raccoons (Cain et al. 2003; Foresman 2004; Meaney et al. 2007; Martinig & Bélanger-Smith 2016) (Figure 93). Shelves should be well-connected to the ground surface with an entrance ramp or similar. There may be some maintenance concerns about using bolt-on metal brackets for metal shelving due to shelves becoming dislodged. Some transportation agencies prefer molded concrete shelving, which would require construction prior to installation of drainage culverts in roads (Gunson & Huijser 2019a).

Figure 92. Pathway for large mammals in an underpass (bridge) primarily designed for water (stream), US Hwy 93 S, Bitterroot Valley, Montana, USA.

Figure 93. Shelf for small mammals in culvert originally designed for hydrology only, US Hwy 93 South, Montana, USA.

- For small- and medium-sized species (up to marten and rabbit size), a minimum walkway width of 0.5–0.7 m (1.6–2.3 ft) is recommended, with a preferred walkway width of about 1 m (3.3 ft) (Huijser et al. 2008c). A dry ledge width larger than 0.5 m (1.6 ft) has been recommended for successful carnivore crossings (Craveiro et al. 2019). A minimum clearance between the walkway and the ceiling of an underpass is about 0.6 m (2 ft) or greater (Huijser et al. 2008c).
- The surface of the walkways should consist of material that animals will not slip on. In some situations, where erosion danger is low, soil may be placed on the walkways (Huijser et al. 2008c) (Figure 94).

Figure 94. Imprints in concrete surface in wildlife underpass to make it less slippery for wildlife, US Hwy 93 S, Bitterroot Valley, Montana, USA.

- A berm the length of the underpass can be added to an underpass that contains water; water can rise while still allowing wildlife to use the berm.
- If drainage culverts are placed and shelving cannot be implemented, small dry pipes can be installed on higher ground adjacent to the drainage culverts. Dry pipe culverts can also be placed not only adjacent to drainage culverts but interspersed between drainage culverts if spacing is not adequate for the target species, to improve connectivity for small mammals (Gunson & Huijser 2019a).

6.6. Additional Considerations for Reptiles and Amphibians

- Underpass structures vary in size from small diameter culverts (e.g. 2 ft in diameter) to box culverts (2-3 m wide and high), to large underpasses (e.g. 7 m wide, 4-5 m high) up to bridges (e.g. 30-100 m wide or more) or elevated road sections (Langton & Clevenger 2020). Blockage of underpasses with leaves and other dead plant material, larger branches, logs, and other debris carried by water in a stream or river, and snow can be an issue, especially for relatively small culverts (Ford & Clevenger 2019; Schroder & Sato 2017; Langton & Clevenger 2020) (Figure 95).

Figure 95. Tumbleweed blocks culverts, primarily for hydrology, but also for Mojave desert tortoise (*Gopherus agassizii*), Hwy 58 near Kramer Jct, California, USA.

- Abiotic factors influence passage use by reptile and amphibian species. Because these species are cold-blooded, their body temperatures can be highly sensitive to temperature changes as well as moisture levels. Light levels can also influence use even for nocturnal species including many amphibians and some reptiles. Structures must be designed to match ambient environmental conditions given the lack of research for most species (Brehme & Fisher 2021; Langton & Clevenger 2020).
- Micro passages (<3ft/1m) with small grates or openings on the top on the road surface can provide effective crossings for reptile and amphibian species in places where larger structures may not be technically or economically feasible (Brehme & Fisher 2021) (Figure 96).

Figure 96. Amphibian tunnel with open slotted roof and barrier or wall for amphibians, integrated into roadbed, Deelenseweg, between Hoenderloo and Arnhem, Gelderland, The Netherlands.

- Passage substrate is critical and should be as similar as possible to the surrounding soil in terms of moisture and temperature. Untreated cast concrete floors may release efflorescence that can leach and burn amphibians' skin. Corrugated metal can be hard to navigate for some species, and because of its conductive properties metal can become much hotter or colder than the ambient environmental conditions and potentially be harmful (Brehme & Fisher 2021; Langton & Clevenger 2020).
- Openings such as a semi-open roof or grates in an underpass allows for more similar conditions inside and outside an underpass (Figure 97). The latter is often an integral part of the design of an amphibian tunnel or culvert (Andrews et al. 2015; Langton & Clevenger 2020). However, run-off from the road containing toxins may be a concern.

Figure 97. Opening (with bridge grate cover) in median to allow light and moisture in the wildlife underpass Hwy 331 Hwy 83 near Freeport Florida USA.

- Placement and spacing of crossing structures are critical for reptiles and amphibians. This can be related to the specific habitat and environmental requirements of the species, and well as the ability and willingness of species to travel along fencing. Ottburg and van der Grift (2019) found that the common toad, *Bufo bufo*, turned around after an average of 50 m if they did not reach a crossing structure. Similarly, Brehme & Fisher (2021) found that California tiger salamanders were only willing to travel an average distance of 40m before "giving up", and Yosemite toads were only willing to travel an average of 52m. This means that in crucial movement areas safe crossing opportunities need to be provided very frequently. Moreover, insufficient number of suitable crossing structures can cause a population crash (Ottburg & van der Grift 2019).

6.7. Enhancing Existing Structures

- Small animals may use existing passages not originally designed for wildlife, such as drainage culverts that were installed to convey water. The structures need to be evaluated to assess whether they are in the correct location and are designed adequately to meet the passage criteria of the target species. Several passage assessments have been developed for small animal passage (Kintsch & Cramer 2011; Langton & Clevenger 2020; Brehme & Fisher 2021).

- In some cases, an existing passage will not require any modifications other than supplementary exclusion fencing, such as the addition of both temporary or permanent exclusion barriers and/or funneling guide walls to direct small animals to existing structures (Figure 98).

Figure 98. Turtle fence tied into an existing culvert for hydrology, US Hwy 83, Valentine National Wildlife Refuge, Nebraska. The camera monitors potential turtle crossings at the culvert.

- Drainage structures are generally constructed in lower wet areas, often along streams or adjacent to wetlands, and are only functional for small animals that occur in or can move through this type of habitat. However, natural substrate and stream dynamics such as water velocity are critical. Smaller animals that move in relatively dry upland habitat will require designated structures installed in higher ground that remain dry when drainage structures are filled with water. Dry wildlife passage opportunities are created through the installation of concrete, wood, and metal shelves into the existing structure, as discussed above.
- To facilitate and enhance use of existing structures by small animals, create or restore habitat such as vegetation, natural substrate, and water sources at crossing approaches, in medians, inside structures, and on top of structures (Gunson & Huijser 2019e) (Figures 99-101).

Figure 99. An existing underpass for a low volume road under a 4-lane A27 motorway, near Hilversum, The Netherlands. The structure was made more suitable for small animal species by placing rows of root wads along the sides.

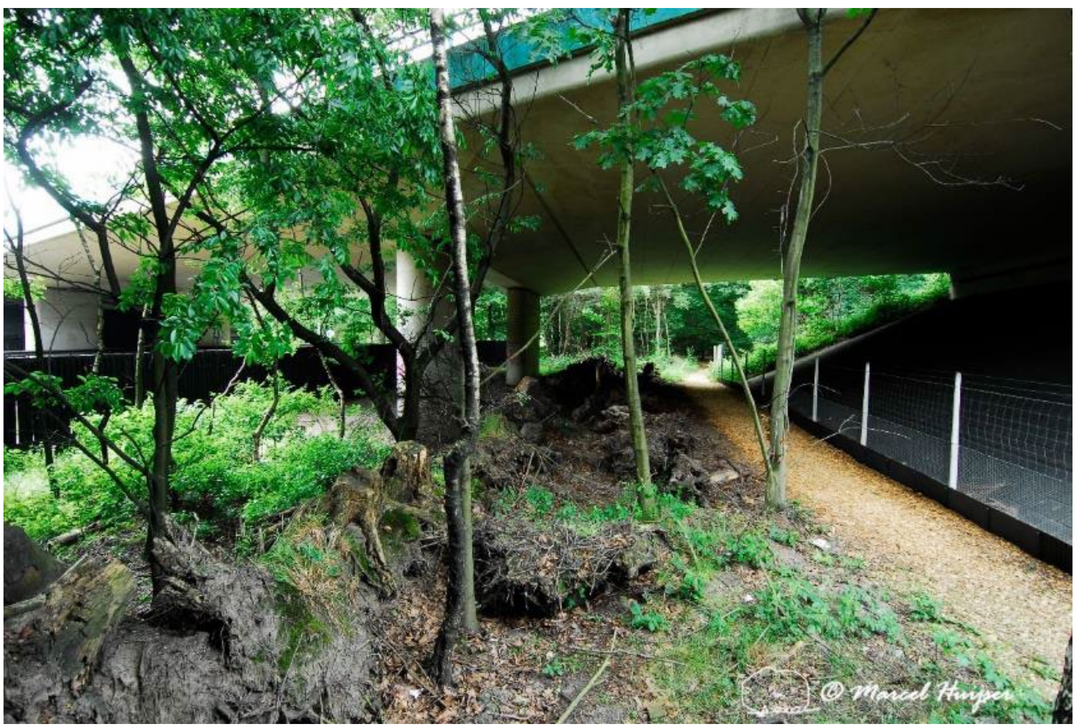

Figure 100. A provincial road crossed under the 4-lane A27 motorway, near Hilversum, The Netherlands. The structure was made wider to anticipate potential future additional lanes. Instead, this space was used to create habitat for small animal species. Note the black screen on the left that reduces light and other visual disturbance originating from the provincial road. The trail on the right is for non-motorized traffic, including equestrian use.

Figure 101. A bridge across the A28 motorway near Utrecht, The Netherlands. One of the lanes was later devoted to habitat for small animal species, including invertebrates.

- In some cases, screens are placed at culvert entrances to deter debris from plugging culverts or to inhibit other wildlife such as beavers from damming inside the structures. Problematically, these screens may trap other wildlife and block animals from entering the culverts. One potential solution includes modifying the screen (i.e., changing the mesh size to allow permeability of the target species while still excluding debris and beavers). Other solutions include using flow devices, diversionary dams, and fence barriers strategically placed to deter beavers from damming culverts and entrances. Wildlife passage must be considered in these solutions, and include integration of a gap, gate, or door in the diversionary barrier (Danby & Gunson 2020).

6.8. Fence-Ends

- Effective barrier-end treatments are required to reduce direct road mortality at or near fence-ends. The best fence-end treatment is to extend a fence beyond the road crossing hotspot and adjacent buffer zone, and to tie the fence-end into an appropriate feature, such as a concrete bridge abutment, or rock cliff. If this is not possible, then, technical designs such as curved ends that limit crossings at or immediately beyond a fence-end are advisable (Gunson & Huijser 2019f).
- For reptile and amphibian species, turnarounds can be effective at reducing fence-end runs by redirecting animals back along the fence line towards the safe crossing opportunity, or at least directing them away from the road (Figure 102). Turnarounds should not be angled and should be smooth curves. The turn-back should be at least 3ft/0.9m from the

barrier and would ideally be 6ft/1.8m-15ft/4.5m long and 6ft/1.8m wide and would curve back in towards the barrier to direct animals back along the fence to a safe crossing opportunity (Langton & Clevenger 2020; Brehme & Fisher 2021).

Figure 102. Though not meeting the recommended specifications for a "turn-around fence-end", this is an attempt at discouraging turtles from crossing the road in high numbers at the fence-end, US Hwy 83, Valentine National Wildlife Refuge, Nebraska, USA.

- Brehme and Fisher (2021) found that >90% of lizards, snakes, and toads and 69% of small mammals were redirected back towards the fencing after leaving a turnaround.
- Ideally the barrier ends beyond where the suitable habitat is of the target species (Langton & Clevenger 2020).
- Treatments are also needed where fencing intersects with access roads, driveways, or other locations where there is another feature that bisects the barrier (Figures 103-105). Cattle guards or other similar structures can be used to stop animals from crossing at-grade, however these must include openings on the sides or ramps to allow animals that fall into the pit to be able to escape back to the safe side of the fence.

Figure 103. A gate for pedestrians and bicyclists at a barrier wall for amphibians, The Netherlands. The rubber flap is designed to keep common toads (Bufo bufo) from crawling under the gate and gaining access to the main road.

Figure 104. Combined drainage and escape for small animals under wildlife guard, Arizona, USA. The openings on the side allow for drainage under the culvert. The openings also allow invertebrates, amphibians, reptiles, small mammals and other species that may fall in between the metal bars to escape. For wildlife guards that have a fully enclosed pit with contiguous walls sometimes wooden planks or metal strips are attached, allowing animals to climb out of the pit.

Figure 105. Escape ramp for small animals from pit under wildlife guard National Park Hoge Veluwe, The Netherlands.

6.9. Jump-Outs, Escape Ramps or One-Way Gates

- Wildlife jump-outs and one-way gates have been constructed for small and medium-sized mammals, as well as for reptiles and amphibians (Figures 106-107). The height of the escape ramps will be determined by the barrier height and as well as the behavioral characteristics of the target species. (Kruidering et al. 2005; Langton & Clevenger 2020).
- Goldingay et al. (2018) documented that the effectiveness of jump-outs, escape ramps, or other right-of-way exits for small animals is unevaluated, and preliminary documentation suggest that these structures may provide more harm than good (Huijser & Gunson 2019). However, Brehme and Fisher (2021) found that earther ramps and modified rectangular plastic mesh cones did allow small animals including reptiles and amphibians to escape the road corridor and move back to the safe side of the barrier. They do note that the modified rectangular plastic mesh cones could be an entrapment hazard for some species and should only be considered in specific scenarios (Langton & Clevenger 2020; Brehme & Fisher 2021).

Figure 106. Wildlife fence and jump-out for medium sized mammals and roe deer, along A28 motorway, near Spier, Drenthe, The Netherlands.

Figure 107. Escape gate for Eurasian badger (*Meles meles*) in wildlife fence Harderwijk, The Netherlands. Note that these types of gates are often left open because of debris which threatens their functioning.

6.10. Implementation/Construction of Fences and Other Barriers

- Have a road ecologist oversee fence installation to reduce the likelihood of installation errors. Once installed, installation errors are hard and expensive to correct, or the errors may never be corrected at all. This can severely jeopardize the effectiveness of the mitigation measures.
- Make sure no gaps or other weak points in the fence occur because of installation errors or challenges.
- Make sure that no gaps remain where the fence connects to the ground. If a dig barrier is added, this is less likely to be a concern.
- Note that the digging of a trench for a dig barrier may require erosion control measures to reduce the probability that sediments end up in streams. Erosion control measures will likely add costs to the installation of a dig barrier (Huijser et al. 2015a).
- Although material types and sizes considerations are essential, often more important to the success of a fencing project are the more subtle details of how the fence is constructed. For example, the plans and specs could specify the maximum gap below the wire mesh fence and the natural ground, but not specify this requirement for vehicle access gates. For instance, a vehicle gate installed on uneven ground that has a large gap on one side may allow animals to enter the fenced road corridor which threatens the effectiveness of the entire set of mitigation measures (Huijser et al. 2015a).

6.11. Implementation/Construction of Wildlife Crossing structures

- Riprap is often used at entrances of culverts and pilings; however, riprap can impede many species from entering into a culvert. Entrances into structures should be clear of rock sizes that impede target species, or spaces between riprap could be filled with smaller material for more even substrate (Jackson et al. 2015; Langton & Clevenger 2020; Brehme & Fisher 2021) (Figure 108).

Figure 108. Riprap in front of culverts to reduce erosion, but the boulder are a barrier to Mojave desert tortoise (*Gopherus agassizii*), I-11, near Boulder City, Nevada, USA.

- Erosion and sedimentation control measures need to be put in place at steep slopes and low-lying wet areas, especially with flowing water. Use natural products that decompose. Do not use plastic or nylon netting as animals may get entangled and die.
- It is helpful to minimize impacts to existing vegetation and soil during construction, to reduce effort in restoring cover and soil type, especially in sensitive environments. Restrictions for where machines and personnel can go can help minimize vegetation removal and soil and hydrology impacts during the construction of a bridge or other structure.
- A tight connection between crossing structures and wildlife fence is essential. Where fencing meets tunnels or other wildlife crossing structures, it is advisable that fence material is well connected to the wing walls or sides of the structures, not allowing any gaps where they meet. Where fences meet drainage culverts, they should either pass above or integrate the culvert into the fence (Clevenger & Huijser 2011).

6.12. Implementation/Construction of Jump-outs or Escape Ramps

- One-way escape gates have been designed for medium sized mammals such as the Eurasian badger (Kruidering et al. 2005). These one-way gates are made of aluminum and are set at an angle, allowing gravity to automatically close the gate. These gates are vulnerable to damage and debris keeping the gates from closing properly. If used, to minimize debris and vegetation growing around such one-way gates, it can be effective to install them on a concrete slab (Huijser et al. 2015a).
- Jump-outs or escape ramps need to be provided so that animals that have entered the fenced road corridor can get back to the safe side of the fence.

6.13. Operation and Maintenance of Fences and Other Barriers

- Without effective fence maintenance, wildlife fences typically become ineffective quickly (Figure 109). This can severely jeopardize the effectiveness of the mitigation measures. A maintenance plan should be developed in the early phases of a project before implementation. Adequate funding and capacity must also accompany these plans so that they are more likely to succeed and reach the stated objectives.

Figure 109. A barrier wall for common toads (*Bufo bufo*) has collapsed, The Netherlands.

- All barrier materials are subject to "wear and tear" maintenance concerns such as holes, burrowing, wash-outs, erosion, vegetation overgrowth, falling trees, vandalism, tampering, car crashes, and damage from mowing and snow removal (Gunson & Huijser 2019f) (Figure 110).

Figure 110. An animal (probably a nine-banded armadillo (*Dasypus novemcinctus*)) dug a gap under a wildlife fence. The burrow is visible on roadside of the fence, SP-225 motorway, near Brotas, São Paulo, Brazil.

- Time spent in initial planning, consultation, and retaining experts reduces the need for maintenance and increases probability of effectiveness. More durable materials, careful and robust installations, as well as educating maintenance workers will help optimize routine maintenance procedures.
- Routine maintenance, such as vegetation clearance, will always be required and must be budgeted for and allocated to responsible agencies early in the planning stages. Implement fence inspection and maintenance programs.
- Fence maintenance is typically not a priority for road maintenance crews. Consider including maintenance requirements in contracts with toll road companies or outsourcing fence inspection and maintenance along state and federal highways.

6.14. Operation and Maintenance of Wildlife Crossing Structures

- A maintenance protocol for wildlife crossing structures and fencing should be created; maintenance needs for right-of-way along structures are usually different from right-of-way or shoulders of most roads without structures. Vegetation needs to be mowed in the clear zone, and sometimes also alongside barriers. Thus, mowing schedules are required for each location. Small animal fencing material may be more fragile than other fencing material and requires careful maintenance. Alternatively, more robust barriers can be designed and installed.
- Crossing structure functionality can be compromised by erosion, flooding, and overgrown vegetation and debris and garbage blocking the entrances (Figure 111). Blockage of underpasses with leaves and other dead plant material, larger branches, logs, and other debris carried by water in a stream or river, and snow can be an issue, especially for relatively small culverts (Ford & Clevenger 2009; Schroder & Sato 2017; Langton & Clevenger 2020). Monsoon season in some areas can lead to soil accumulation inside small culverts, which can limit culvert use by wildlife (Chen et al. 2021).

Figure 111. A culvert blocked by rocks under the road to the overlook, Childs Mountain, Cabeza Prieta National Wildlife Refuge, Arizona, USA.

- Shelving systems and ramps installed in an underpass may require annual cleaning for debris or if the units have become dislodged (Huijser et al. 2021).
- In some cases, screens may be added to culvert entrances to deter debris and beavers from damming or plugging culverts. Because these screens may trap other wildlife and block

animals from entering through culverts, thought must be given to the design, such as mesh size or spacing of rods.

- At structures with water, specific maintenance is needed to ensure scouring or erosion does not create a "perched entrance" or other barriers that prevent the target animal access to a structure (Langton & Clevenger 2020) (Figure 112).

Figure 112. A culvert with a heavily eroded outflow near Indian Springs, Nevada, USA. Inaccessible to desert tortoises.

- Vegetation that is too dense and obscures the visual opening or prevents small animal passage of a culvert should be selectively removed or thinned (Smith et al. 2015; Langton & Clevenger 2020). Vegetation such as cattails and common reed may need to cleared routinely around structures with water.
- Depending on the climate and soil, plantings on wildlife overpasses and approaches to the structures may require watering for the first few years.

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8. APPENDIX: HOME RANGE SIZE AND DIAMETER HOME RANGE FOR LARGE WILD MAMMAL SPECIES FOR THE SPACING OF WILDLIFE CROSSING STRUCTURES.

Species	**Home range (ha) and diameter (m)**	**Source(s)**
Mountain lion	4,000 ha 7,138 m	3,500 ha (range 1,900-5,100 ha) for adult females in summer and 2,600 ha (range 1,400-4,300 ha) in winter (Spreadbury et al. 1996), 6,730 ha for females (review in Lindstedt et al. 1986), 9,700 ha (range 3,900-22,700 ha) for adult females in summer and 8,700 (range 3,100-23,900 ha) in winter (Ross & Jalkotzy 1992)
Wolf	50,000 ha 25,238 m	6,250 ha (range 700-6,800 ha) (review in Lindstedt et al. 1986) 65,000 ha (Fritts et al. 1997)
White-tailed deer	70 ha 944 m	70.5 ha for adult females in summer (Leach & Edge, 1994), <80 in summer (Mundinger, 1981), 60-70 ha for females in summer (review in Mackie et al. 1998), 89 ha (range 17-221 ha) for females in summer and 115 ha (range 19-309 ha) in winter (review in Mysterud et al., 2001)
Mule deer	300 ha 1,955 m	301 ha on average for males and females in winter (D'Eon & Serrouya, 2005), 90-320 ha for adult females in summer and 80-500 ha in winter (review in Mackie et al. 1998), 617 ha (range 25-4,400 ha) for females in summer and 1,267 ha (range 32-9,070 ha) in winter (review in Mysterud et al., 2001).). Long distance seasonal migration can occur.
Elk	5,000 ha 7,981 m	3,769 ha (range 820-9,520 ha) for females in summer and 181 ha (range 152-210 ha) in winter (review in Mysterud et al., 2001), 5,296 ha for adult females in summer and 10,104 ha in winter (Anderson et al., 2005), 8,360-15,720 ha for elk populations (Van Dyke et al., 1998). Long distance seasonal migration can occur.
Moose	2,500 ha 5,643 m	2,612 ha (range 210-10,300 ha) for females in summer and

		2,089 ha (range 200-11,300 ha) in winter (review in Mysterud et al., 2001)
Pronghorn	2,500 ha 5,643 m	656 ha on average (range 938-3,773 ha (Clemente et al. 1995) winter 5,550 ha, summer 1,970 ha (Jacques et al. 2009). Long distance seasonal migration can occur
Bighorn sheep	900 ha 3,386 m	541 ha for females (review in Demarchi et al., 2000), 920 ha (range 650-1,140 ha) for females in summer and 893 (range 880-1,320 ha) in winter (review in Mysterud et al., 2001), 640-3,290 ha (review in Demarchi et al., 2000)
Mountain goat	300 ha 1,955 m	280 ha for adult males, 480 ha for adult females (Singer & Doherty, 1985)
Caribou	40,000 ha 12,739 m	38,500 ha (range 12,800-73,700 ha) (Mercer et al., 2004), 30,000-150,000 ha (Dalerum et al., 2007). Long distance seasonal migration can occur.
Bison	20,000 ha 15,958 m	adult females 124,050 ha, older adult males 17010 ha (Larter & Gates 1994). Long distance seasonal migration can occur.
Black bear	4,000 ha 7,138 m	1,960 ha for females (Young & Ruff 1982), 5,960 ha (range 2,300-16,000 ha) for adult females (McCoy, 2005)
Grizzly bear	25,000 ha 17,846 m	22,700 ha (range 3,500-88,400 ha) for adult females (Gibeau et al., 2001), 28,500 ha (112-482 ha) for adult females (Servheen, 1983)

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