AMPHIBIAN AND REPTILE HIGHWAY CROSSINGS

State of the practice, gap analysis and decision support tool

A Literature Review

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CONTENT

Cover photograph: One of the passages with angled wing walls built at Ventana Way, Seascape Uplands, Santa Cruz in 1999 to mitigate habitat loss and road construction for the Santa Cruz long-toed salamander. Six passages and 300 m of barrier are present.

SUMMARY

This review investigates the English language literature concerning road impact mitigation passages and barrier systems for amphibians and reptiles. Aspects of 52 studies, some of multiple locations, concerned 125 individual taxa (75 reptile and 50 amphibian species or sub-species) were examined. Studies were from mainly Europe and North America but also South American and Australasia.

Snakes, lizards and frogs were the most studied of the seven discrete species groups, each representing about 20-25% of taxa, with 13 salamander/newt taxa, five turtle and two of tortoise studies. North America is the only location where detailed investigations of turtle passages have been made and desert tortoise studies are two of only three tortoise passage studies worldwide.

Information from each paper was placed into three study or 'knowledge area' categories; *passage construction and use*, *passage environmental variables* and *barrier construction and use*. From the 52 key publications there were 170 individual knowledge areas in these categories. For these, there was a little over twice the number of publications for amphibians as for reptiles, however the amount of information on barriers was similar and overall the level of information was not that different; 45% were for reptiles and 55% amphibians. Only around half of the studies addressed the quality of passage environment. Most studies addressed single locations and were from temperate regions, while less than 10% were from tropical or sub-tropical habitats.

Overall, the greatest amount of information of passages and barriers was for frogs and salamander/newts, followed by turtles, toads and snakes. Lizards and tortoises had the least amount of coverage. Generally the studies were spread evenly across taxa with small sample sizes for any single species, but a few species had more than five studies.

Crossing structures were divided into five categories, largely reflecting the width of passage over or under roads. There were less than five studies representing large overpasses and other bigger crossing types, while almost all considered passages of less than 3.0 m span and often smaller. There has been relatively little study of the use of large and small bridges for herpetofauna dispersal across roads.

Information regarding barrier systems was more comprehensive and complete than for the different types of passages. There exists a wide range of stand-alone fencing types and more structural built-in guide walls. Preliminary descriptions of construction materials have been made and this will inform the final Best Management Practice (BMP) output.

Results suggest than in most cases road impact mitigation has not been set against a quantitative objective but simply to reduce road mortality. Evidence suggests that large passages enable more crossings and that small passages may often have an acceptance rate of just a small proportion of a population that is subject to road severance. Detailed studies are few, although new camera technology makes future studies more feasible. Some controlled experiments manipulating key variables are indicative in showing effect and trends, however studies often have small sample sizes with low confidence levels in their conclusions.

A total of 161 Californian taxa (including subspecies) were scored for road risk within both terrestrial and aquatic habitats, and were assigned categories of risk (Very High, High, Medium, Low, and Very Low). Most noticeable for the 65 Very High and High Risk California amphibian and reptile species is that snakes dominate the two categories with 58% of the total species. All of the California turtle species (3) and the tortoise species (1) are represented but relatively few lizards. Over two-thirds of the Very High and High Risk species are reptiles and the remaining one third of species are split more or less evenly amongst the three amphibians groups (8-11%).

The nature and frequency of different crossing types worldwide, in North America and in California is reviewed with comments on the use and availability of engineered (purpose-built) and non-engineered (mainly road drainage) culverts in the landscape.

Generally the literature reflects a widely spread and low-inference scientific knowledge base regarding road mitigation with amphibian and reptile passages and barrier systems and the extent of their use. Locally in California information on amphibian and reptile mitigation projects is confined to less than 20 locations within the State Highway System with some having no written materials available. Further, interviews with academic researchers and environmental consultants may obtain further information and some reports may be confidential and unavailable. There are probably other herpetofauna crossing mitigation systems off the highway system, e.g. on private lands, so those systems detected to-date may not be a complete.

Considering there are numerous amphibian and reptile passages and barriers throughout the world, relatively few have undergone rigorous study to evaluate their effectiveness. Use of existing passages under highways that are created by river bridges and drainage culverts have largely not been evaluated for their role in helping to maintain genetic and population connectivity for herpetofauna. Therefore, going forward there is both a need for properly designed studies to evaluate the effectiveness of purpose-built (engineered) and non-engineered road structures that provide passages and barriers, as well as conducting studies (controlled experimental or field settings) to directly measure, test and compare existing and potential road permeability.

The effectiveness of passage and barrier designs for maintaining species movement and population connectivity may also require further research. Information regarding passage qualities, including size (diameter and length), light levels (by day and night), moisture and substrate (passage floor) may be used to help identify optimal recommendations for species groups or those that have similar life history and space use patterns. Most important is the identified need to define what kind of passage use is necessary in each situation and the measurable success criteria for the passage outcome. This is rarely defined and new categories are proposed for system designers.

This review defines major information gaps of what is known about the effectiveness of barrier and passage systems and is presented by species groups. We identify multiple lines for future research investigation. Finally, we review current Best Management Practice (BMP) and Guidance Manuals for herpetofauna crossings, which are generally limited in scope and content. Information from our global literature review, current research studies and BMP's, and the risk assessment will be used to guide future research and towards developing California BMPs for sensitive amphibian and reptile highway crossings.

1. INTRODUCTION

Objectives

Amphibians have received increasing attention since a declining global populations crisis was first reported in the late 1980s (Adams et al. 2013) with the amphibian extinction rate estimated to be 211 times the background rate (McCallum 2007). Reptiles are declining on a global scale as well, and may be generally in even greater danger of extinction worldwide (Gibbons et al. 2000). There are many significant threats to amphibian and reptile populations including habitat loss and degradation, habitat fragmentation, environmental pollution, disease, climate change, and road mortality from traffic or entrapment in road drainage structures. In California, 24 out of 154 herpetofauna species (16 %) are currently listed as endangered and threatened. These include 15 amphibian and 9 non-marine reptile species.

Roads and road networks have many detrimental effects at the individual, population and landscape level (Marsh and Jaeger 2015, Langen et al. 2015). Literature reviews of road effects on other vertebrate taxa have been published (Trombulak and Frissel 2000, Glista et al. 2009, Kociolek et al. 2011), however, there are few detailed literature reviews on road impacts on amphibian and reptiles in the last decade (Andrews et al. 2006, 2015; Beebee 2013).

The road environment may attract some amphibians and reptiles, for example, road verge ditches can provide amphibian breeding sites (Matos et al. 2012) and roads, verge slopes and embankments can provide reptile basking places. Verge slopes and embankments can also provide food sources (Edgar et al. 2010, Andrews et al. 2015) and may link patches of habitat (Hambrey Consulting. 2013). In order to address the deleterious effects of roads, government transportation agencies have, over several decades tried to mitigate road impacts by providing dispersal passage and barrier structures (Langton 1989, 2002, 2015; Schmidt and Zumbach 2008, Jackson et al. 2015, Hammer et al. 2015, Langton et al. 2015).

Brehme and Fisher (2017) reported that in California, 100% of turtle and tortoise species, 72% of snake species, 64% of toad species, 36% of frog species, 18% of lizard species, and 15% of salamander species are at high or very high risk from negative road impacts within their terrestrial and/or aquatic habitats.

Although wildlife passages and barriers have been constructed on roads in many countries and there have been general overviews to describe them, there is now a need to compile and synthesize more detail of the effectiveness of designs for amphibian and reptile species. Efforts in Europe and North America have been more extensive and over longer periods than elsewhere but interest is widening. Reviews of scientific literature are a starting point and valuable as guidance for research and management. Reviews can also inform the creation of management recommendations for road impact mitigation and compensation.

The purpose of this literature review is to describe the state of the science and practice of reducing, mitigating and compensating road impacts for amphibians and reptiles. We review background information, describe current threats and impacts and with reference to a road risk assessment of California amphibian and reptile species. We synthesize the efficacy of various passage mitigation measures as they relate to amphibians and reptiles; worldwide, in North America and in California. Last, we review published Best Management Practice (BMP) - the technical guidelines produced for mitigating road impacts on amphibians and reptiles. The BMP review will be the basis for developing a framework for the main project output; a Caltrans BMP for mitigating road impacts on sensitive amphibian and reptile species and herpetofauna communities in general.

2. METHODS

We reviewed reports and peer-reviewed articles focused on methods of mitigating the impacts of roads on amphibian and reptile populations using built structures; principally passages and barriers. Herpetofauna were divided into seven broad taxonomic species groups; snakes, lizards, tortoises, turtles, frogs toads and salamanders/newts. Passages were divided into five categories, generally reflecting passage size; types 1-5 (Langton et al. 2015).

We conducted a literature search through Wiley Online Library, GreenFILE, Scopus, Web of Science, ScienceDirect, and BioOne, Proceedings of the International Conference on Ecology and Transportation, and Google Scholar, and relevant ecological and herpetofauna journals directly.

We searched the databases (titles, keywords, and abstracts) for (reptile* or amphibian* or snake* or lizard* or salamander* or turtle* or tortoise* or frog* or toad*) AND (underpass* or culvert* or tunnel* or overpass* or ecopassage* or "wildlife passage*").

Because of the relative scarcity of information we searched the literature globally, but were primarily concerned with reviewing material that had implications for native California species. So for example, information on crocodilians has not been included, although information on some potentially invasive non-native species has been included if it is mentioned.

We provide scientific names for amphibian and reptile species reported in the literature cited in Appendix A.

3. THREATS POSED TO AMPHIBIANS AND REPTILES BY ROADS AND TRAFFIC

Table 3.1 provides examples of and key references to impacts on amphibian and reptile groups identified for this review. The aim is not to be exhaustive but give examples for each of the species groups, in order to demonstrate the range of impacts and how they have been addressed in published studies of practical mitigation. These are important to register because many aspects of threat have a bearing on the design and construction of mitigation passages and barriers. The key references consider aspects of how roads affect amphibian and reptiles at the level of individuals and populations. These impacts consist of direct and indirect effects that manifest change in demographics, genetics and long-term population conservation (see Jochimsen et al. 2004, Gibbs and Shriver 2005, Andrews, et al. 2008, Beebee 2013, Marsh and Jaeger 2015).

3.1. Direct threats

Vehicle-related mortality

Many vertebrate field studies touch on the extent to which animals are killed moving onto or across roads, being hit by moving vehicles or killed by air pressure waves. Amphibians, (particularly frogs, toads, salamanders and newts) and some reptile species (snakes and freshwater turtles) suffer mass mortality from road traffic. This may occur, particularly for amphibians during seasonal breeding movements; either adults converging on or within near-road wetlands or adults and emerging young of the year leaving a breeding area. Some amphibian and reptile species may have relatively low thresholds for population-level impacts resulting from road traffic mortality.

Many reptiles such as garter snake and rattlesnake species cross roads slowly and may be attracted to the warmth of roads for thermoregulation. They may cross roads in large numbers due to the seasonal use of large communal denning/overwintering areas that are the focus of mass, synchronised emergence at certain times of the year.

Traffic mortality can impose a direct and significant negative effect on local density of anurans. Fahrig et al. (1995) discussed the already extensive anecdotal information and placed accounts of road traffic extirpating populations into a quantitative context. This was done by demonstrating density dependant relationship using a large-area study and relating road traffic and residual amphibian densities. Anuran density was shown to decrease with increasing traffic intensity. A literature review by Fahrig and Rytwinski (2009) found primarily negative and neutral effects of roads on anuran abundance. In a subsequent analysis, amphibians with lower reproductive rates were found to have greater negative road impacts than those with high reproductive rates (Rytwinski and Fahrig 2012).

High road mortality (e.g. Klauber 1931, Rosen and Lowe 1994, Jones et al. 2011), decreased genetic diversity (Clark et al. 2010, Hermann et al. 2017), reduced abundance near roads (Rudolph et al. 1999, Jones et al. 2011), and reduced road mortality of species as a result of passages and barriers have been documented for many herpetofauna species (Dodd et al. 2004, Colley et al. 2017).

Snakes and chelonids (tortoises and turtles) are similar in that many move long distances (home range and/or migratory), tend not to avoid roads (or are attracted to for thermoregulation), are long lived, and have relatively low fecundity in comparison to other herpetofaunal groups. Because of these traits, chelonids and snakes have been identified as being particularly susceptible to negative population effects from roads (Gibbs and Shriver 2002, Andrews et al. 2015a, Jackson et al. 2015). High road mortality resulting in lower abundance near roads ("road effect zones") have been documented for these groups (Rudolph et al. 1999, Jones et al. 2011, Boarman and Sazaki 2006; Peaden et al. 2016). For aquatic snakes, roads may account for mortality of 14–21% of the population per year for the wide-ranging terrestrial, copperbelly water snake (Roe et al. 2006).

Lizards generally appear to have a lower tendency to cross paved roads with high traffic volumes (Brehme et al. 2013). However, paved roads with low traffic volumes may be used for basking where lizard species can be vulnerable to mortality (Tanner and Perry (2007).

Physical barriers and genetic fragmentation

Over the last 20 years, as molecular investigation and research techniques have advanced, accounts of road-related herpetofauna mortality have increasingly made reference to genetic study (Beebee 2013). Several studies have sampled individual animal DNA using blood or body tissue, to compare genetic diversity, relatedness, and fitness/signs of inbreeding in road-impacted and control populations.

Marsh et al. (2008) sampled the effects of roads on patterns of genetic differentiation in red-backed salamanders. They found detectable differences for wide and busy roads, but not for smaller two-lane roads. For terrestrial snakes, microsatellite analysis of a western diamondback rattlesnake population in Sonoran Desert habitat, divided for over 50 years by an Interstate highway, showed measurable genetic distancing either side of the road (Herrmann et al. 2017).

Studies of a large multi-species herpetofauna community (44 species of reptile and amphibian) crossing a busy 4-lane highway at Lake Jackson, Florida, demonstrated the very high vulnerability of some species to road traffic (Aresco 2005a, 2005b). These included the slow-moving turtles, indicating that individual crossing speed strongly influences crossing survival. Direct mortality of one or more species and depletion may have subtle yet profound long-term impacts upon the adjoining habitat to some considerable distance.

Table 3.1. Examples showing the range of road transportation impacts for the amphibian and reptile species groups investigated.

Herpetofauna category	Key references/examples	Notes
General	Fahrig, et al. 1995. Effect of road traffic on amphibian density.	Recorded Anuran frequency, per km of road decreased with increasing traffic intensity. Frog and toad density (chorus intensity) decreased with increasing traffic intensity. Taken together, traffic mortality seems to have a significant negative effect on local density of anurans.
	Findlay, C.S., and J. Houlahan, 1997. Anthropogenic correlates of species richness in southeastern Ontario wetlands.	A strong positive relationship between wetland area and species richness for all taxa. The species richness of herpetofauna was negatively correlated with the density of paved roads on lands up to 2 km from the wetland and showed a strong positive correlation with the proportion of forest cover on lands within 2 km. Road construction and forest removal on adjacent lands posed significant risks to wetland biodiversity.
	Hels, T. and E. Buchwald, 2001. The effect of road kills on amphibian populations.	Found a significant relationship between amphibian mortality rate and traffic density.
	Andrews, K. M., Gibbons, J. W. and D. M. Jochimsen. 2008. Ecological effects of roads on amphibians and reptiles.	Recent overview of direct effects (road construction & road kills), and indirect effects of habitat fragmentation via population and community level impacts.
	Marsh, M. and J.A.G. Jaeger 2015. Direct effects of roads on small animal populations. In Andrews K. M. et al. 2015.	Concluded six key points: landscape scale effects, mortality vs barrier effects, variability in timing of effects impact, robustness of mitigation efforts, long term impacts with traffic growth, additional impacts that follow roads, fragmentation-based protection analysis.
	Gibbs, J.P. and W.G. Shriver, 2005 Can road mortality limit populations of pool-breeding amphibians?	Modelling study implies that an annual risk of road mortality for adults of >10% can lead to local population extirpation. Mitigation efforts should seek to reduce road mortality rates to below this threshold. For central and western Massachusetts, it was estimated that salamanders would be exposed to at least this threshold level of risk at 22–73% of populations

Herpetofauna category	Key references/examples	Notes
Frogs & Toads	Cosentino, B.J. et al. 2014. Citizen science reveals widespread negative effects of roads on amphibian distributions.	Lowland anuran species richness and individual species distributions were constrained by both road density and traffic volume. Negative effects of roads on amphibians occur across broad geographic regions, affecting even common species.
Salamanders & newts	Marsh, D. et al. 2008. Effects of roads on patterns of genetic differentiation in red-backed salamanders, *Plethodon cinereus*. Ward, R.L. et al. 2008. Effects of road crossings on stream and streamside salamanders.	Microsatellites were used to examine whether six roads (one divided interstate highway, one undivided four-lane highway, and four secondary roads) led to increased genetic differentiation. Genetic distance between populations bisected by an interstate highway was greater than those on the same side of road. For smaller roads, genetic impacts are less obvious than direct effects of mortality and habitat alteration. Salamander diversity and richness was affected by elevation, stream gradient, canopy cover, and the presence of roads. Overall, stream and riparian habitat quality was the most important factor affecting salamander richness. The presence of roads, stream gradient, and elevation received the most empirical support for predicting species' abundances. Roads benefited disturbance-tolerant species but negatively affected other species. Conclusion was that impacts of roads and culverts on habitat should be considered by Federal and State transportation and natural resources agencies during the planning process and addressed through mitigation efforts. Managers should install culverts that are as wide as the stream channel, at grade with the streambed, and dominated by rubble substrate, in order to provide maximum benefit for salamanders.
Lizards	Tanner, D. and J. Perry. 2007. Road effects on abundance and fitness of Galápagos lava lizards *Microlophus albemarlensis*. Painter, M.L., and M.F. Ingraldi. 2007. Use of simulated highway underpass crossing structures by flat-tailed horned lizards (*Phrynosoma mcalli*).	Changing road surface from dirt to paved appears to increase mortality and there is a road influence zone either side of the road where lizard numbers are depleted. Flat-tailed lizard is prone to bask on roads and remain motionless in response to visual threats – hence have no traffic avoidance response.

Herpetofauna category	Key references/examples	Notes
Aquatic snakes	Roe, J.H., et al. 2006. Beyond the wetland border: Estimating the impact of roads for two species of water snakes.	In Indiana, USA, roads may account for mortality of 14–21% of the more terrestrial copperbelly water snake (*Nerodia erythrogaster neglecta*) but only 3–5% mortality in the more sedentary, aquatic northern water snake (*Nerodia sipedon*). The majority (>91%) of road crossings and associated mortality are predicted to occur during overland migrations to other wetlands, suggesting bisecting roads may cause a population sink. A landscape approach to wetland conservation is recommended, that considers not only wetland quality but also nearby terrestrial habitat quality and ensures that terrestrial corridors between wetlands remain permeable and that they offer safe fauna passage.
Terrestrial snakes	Herrmann et al. 2017. An interstate highway affects gene flow in a top reptilian predator *Crotalus atrox* of the Sonoran Desert	Microsatellite (DNA) analysis showed that two subpopulations in close proximity (4 km), but separated by Interstate Highway I-10 in Arizona, since 1955 showed greater levels of genetic differentiation than two subpopulations that were separated by a greater distance (7.0 km) and not by I-10 or any other obvious barriers. I-10 has reduced gene flow in a population of an important reptilian predator of the Sonoran Desert in southern Arizona.
Turtles	Gibbs, J. P. and Shriver, W. G. 2002. Estimating the Effects of Road Mortality on Turtle Populations. Aresco, M. J. 2005. Mitigation measures to reduce highway mortality of turtles and other Herpetofauna at a North Florida Lake. Journal of Wildlife Management 69(2): 549-560.	This is a modelling study using roads and traffic-volume data with simulated movements of small-bodied pond turtles, large-bodied pond turtles, and terrestrial and semi terrestrial ("land") turtles. The model predicted that road networks typical of the north eastern, south eastern, and central USA regions have potential to limit land-turtle populations and to a lesser extent, populations of large-bodied pond turtles. Roads may jeopardize population persistence within road networks typical of the eastern and central United States. Provided strong evidence that turtles cannot successfully cross all four lanes of U.S. Highway 27. 95% of 343 turtles were killed as they first entered the highway adjacent to the shoulder and the remaining 5% were killed in the first two traffic lanes. According to a probability model, the likelihood of a turtle successfully crossing U.S. Highway 27 decreased from 32% in 1977 to only 2% in 2001 due to a 162% increase in traffic volume. Many out of a total of 44 reptiles and amphibians benefitted from the placement of temporary drift/guide fencing.

Tortoises	Boarman, W.I., and M. Sazaki. 2006. A highway's road-effect zone for desert tortoises (*Gopherus agassizii*)	Mohave desert tortoises are depleted in number 400-800 metres either side of a major highway.

3.2. Indirect threats

Environmental alteration

Roads alter soil density and water content, light levels, dust, surface water behaviour, patterns of runoff and sedimentation as well as adding heavy metals (especially lead), salts, organic molecules, gaseous (e.g. ozone) and a range of particulates with plant nutrient value to roadside environments (Forman et al. 2003).

Many of the hydrocarbons (polycyclic aromatic hydrocarbons) released may be carcinogenic to vertebrates. Most amphibians and many reptiles have less skin protection from surface contamination than mammals and birds. Aquatic egg and larval stages of amphibians are particularly exposed to those that are soluble, as may be the more aquatic adults and juveniles. Levels of dilution may influence exposure and risk.

Nitrogen from vehicle emissions and other nutrients such as calcium, magnesium and phosphorus that may promote vegetation growth may influence roadside habitats including aquatic algae and aquatic macrophytes. Enriched growth in unicellular and small aquatic plant life and vegetation may change habitats and promote denser vegetation with lower species richness, with similar knock-on effects to invertebrate richness. These in turn may influence amphibians and reptiles in terms of habitat-use including breeding, basking and feeding opportunity.

A major influence to the road environment in many areas comes from the use of de-icing salts used in freezing and winter conditions and particularly chlorine compounds. Such materials may have considerable ecological effects on freshwater habitats (Langen et al. 2006). For slotted surface passages, road run-off may pass onto the base of the passage and accumulate or otherwise be in contact with dispersing animals (White et al. 2017).

Findlay and Bourdages (2000) indicated that the full effects of roads upon wetland biodiversity including pollution may be undetectable in some taxa for decades. Such time lags they concluded have important implications for land-use planning and environmental impact assessment.

Noise, vibration and light pollution from vehicles and road structures may also alter local conditions considerably and influence amphibian and reptile persistence through sub-lethal effects that may bring about subtle behavioural change, as has been demonstrated by preliminary investigations (Brattstrom and Bondello 1983, Perry et al. 2008, Tennessen et al. 2014).

Road infrastructure

Entrapment of wild animals in road drainage systems is a hidden yet potentially significant impact from roads, including injury and death of individuals that could have population level effects. Road drains or gully pots are vertical chambers next to the curb designed to rapidly remove large amounts of road surface water during rain events. Metal grills at the road surface are wide enough for many small vertebrates to fall through and become trapped (Van Diepenbeek and Creemers, 2012). The chambers have silt and oil retention functions and animals may often escape only into underground pipe/culvert systems where they may starve, be exposed to concentrated pollutants or sometimes discharged into a less suitable area for their survival.

Structures such as barrier fencing and dropped curbs to keep small vertebrates away from and falling into road drainage systems may enable animals to remain in places where they may otherwise be extirpated (Jackson et al. 2015). Elsewhere however use of plastic barriers at construction and maintenance sites to exclude reptiles has result in reptile mortality as well as its prevention. Some fabricated chambers have been replaced by more naturalistic lagoons or swales, sometimes referred to as sustainable drainage structures (SuDS) in designs aimed at surface water attenuation and slower surface infiltration than may be achieved with culverts and storage chambers (Clevenger and Huijser 2009).

The issue of designing escape mechanisms from buried chambers has been addressed formally by government agency in Switzerland (V.S.S. 2009). Simple design adjustments to existing structures (such as small exit ramps and outlet holes with the use of ramps/ladders and 'climb cloth') would potentially allow many millions of amphibians, reptiles (and other fauna) to escape entrapment and premature death each year.

3.3. Vulnerability related to life history

Amphibians and reptiles have certain life history attributes that make them vulnerable to road effects. Species with large range sizes, or long directional movements or 'migrations', tend to be more at risk than less mobile species where annual mortality overtakes recruitment. Some species have low reproductive rates and occur at low densities, exacerbating the road mortality effects on population persistence. Table 3.2. gives examples of life history attributes and road sensitivity of the amphibian and reptile species groups.

3.4 Risk assessment of California amphibians and reptiles

The primary goal of this study was to provide Caltrans (California Department of Transportation) and other planning agencies in California the needed guidance to prioritize road mitigation efforts for amphibian and reptile species. Although there is still a lot to learn about the effectiveness of different designs of road mitigation systems, the use of passage and barrier systems can reduce road mortality and help to maintain connectivity and safe passage across roads for herpetofauna and other wildlife (Jochimsen et al. 2004, Colino-Rabanal and Lizana 2012, Langton 2015).

Because it is currently unrealistic and cost prohibitive to take action on all roadways for all species, it is necessary to focus on those that are most at risk of decline from roads and road related impacts. Populations of such species near to existing or proposed roads can be identified and evaluated for the need of passage and barrier structures.

Table 3.2 Examples of life-history vulnerabilities of amphibian and reptile groupings identified for this study.

Species Group	Life history vulnerability and road sensitivity	Additional vulnerability and road sensitivity
General	Some species are slow-moving and unable to fly over or move fast across roads, having no sense of risk from moving traffic. Many species are crepuscular or nocturnal and move at times humans are driving to and from the work place and places of recreation.	Relatively low powers of dispersal of many species may be exaggerated and result in the fragmentation of populations, leading to genetic separation, population decline and inbreeding.
General amphibians	Many species have mass-linear movements from higher or drier habitat to low lying wetland areas and ponds. Where roads intercept these routes there may be high mortality potential. High reproductive rates in some species may lessen population level effects.	Aquatic phase may render eggs and larvae subject to road pollution impacts. Roads may be routed around wetland edges for scenic reasons, for access or ease of build, in zones where amphibians congregate to breed.
General reptiles	Some species have large range sizes and or mass- linear movements. Denning close to roads may result in mass mortality.	Road surface heat may encourage basking on roads by poikilotherms.
Frogs	Many species congregate and compete when breeding in places with little vegetation cover, leaving them open to mass mortality events. Many do not avoid roads, particularly during rainfall events.	Abundance may be reduced, intensifying predator impacts and reducing effective population size.
Toads	Some species congregate when breeding at the start and end of seasons and may make both long terrestrial and aquatic movements, leaving them open to mass mortality events. Many do not avoid roads, particularly during rainfall events.	In some species, males may sit on a road as it mimics flat open habitat that they prefer in order to locate females.
Salamanders and newts	Slow-moving across roads esp. during rain events with little or no sense of risk from traffic. Most do not avoid roads, particularly during rainfall events. Many species disperse at times of day & night that humans are driving between home, workplace & recreational areas.	Some species are highly sensitive to dry conditions and require the ground to be wet for crossing.
Lizards	Many species have small home ranges & may rarely cross open ground/heavily trafficked roads.	Low dispersal may exacerbate isolation and fragmentation effects.
Aquatic snakes	May move along river banks where roads run parallel. Ability to navigate culverted stream bridges may be limiting to some species and sized individuals if there is a pipe overhang to navigate.	Humans may perceive running over a snake is a public good action.
Terrestrial snakes	Some species congregate while others are wide-ranging so road exposure may be highly varied. Many large bodied snakes have extensive home ranges.	Humans may perceive running over a snake is a public good action.
Freshwater turtles	Roads may be routed around wetland edges for scenic reasons, access or ease of build in edge zones. Where turtles naturally congregate for basking/resting and egg-laying. Turtles regularly exhibit both long in stream movements and lay eggs in terrestrial uplands. Therefore, Roads that cross or parallel ephemeral streams, creeks, and rivers are a threat. See also below for long-lived species.	Sex bias documented in many turtle populations near roads due to roadkill of females that use terrestrial habitat more in order to lay eggs. Aquatic phase may render turtles subject to road pollution impacts
Tortoises	Slow breeders so reaction time to population disturbance is in decades not years. Large home ranges & slow-moving crossing or walking along roads.	Shifting sand and soil may make barriers passable and block passages.

Here we describe a road risk assessment methodology applied to native amphibian and reptile species in California. We also included analysis of subspecies if they have special federal or state protection status. This includes 166 species and subspecies of frogs, toads, salamanders, snakes, lizards, turtles, and tortoise. Rankings and prioritizations such as these can be very subjective. In order to avoid including low risk species that may be favoured by the assessor bias or to unintentionally exclude species that are at high risk but that are less well considered in error, it was important this be done in an objective manner informed by current road ecology literature.

All ranking was based upon a suite of species life history and space-use characteristics associated with negative road effects, as well as species distribution and conservation status. Risk was evaluated for both aquatic and terrestrial connectivity. Evaluation included buffer distances that were calculated to encompass 95% of population movements.

Relative confidence in these distances is given for each species based upon the amount of support from scientific studies. The appraisal solely focused on direct effects of roads as barriers and sources of road mortality and not effects of road construction and maintenance or indirect effects of increased human use of the landscape once a road is in place (see review by Langen et al. 2015).

We assessed the relative risk of California herpetofauna species to negative road related impacts at three scales in a stepwise fashion. We first assessed risk at the scale of an individual animal and then expanded the risk to the population and then to species (Figure 1).

At the individual level, we based road risk primarily upon the likelihood that an individual would encounter one or more roads. We considered this a product of terrestrial and aquatic movement distance (home range, seasonal migrations) and movement frequency (active foragers, seasonal migrants, sit & wait predators vs. sedentary species (e.g. Bonnet et al. 1999, Carr and Fahrig 2001). Because many species are semi-aquatic, movement distance and frequency were scored separately for both aquatic and terrestrial habitats. The overall risk level was determined by the higher score. There is a theorized higher risk associated with depletion effects (i.e. mortality) in comparison to barrier effects (Fahrig and Rytwinski 2009, Jackson and Fahrig 2011). Therefore, additional weight was given to those more likely to move onto a road and experience mortality due to vehicular traffic. Individuals and species may respond differently to roads (attraction vs. avoidance) based upon landscape characteristics, road width, traffic volume and perceived danger (Forman et al. 2003, Andrews 2005, Brehme et al. 2013, Jacobson et al. 2016). To address this we considered factors of habitat preference (e.g. open vs. closed), roads as potential attractants (e.g. for basking), and movement speed. Because a state-wide analysis encompasses extreme variation in road width and traffic volumes, we limited this to twenty percent of the individual risk score.

Population-level road risk was assessed by multiplying individual risk with scores representing 1) the relative proportion of the population at risk and 2) the species ability to sustain higher rates of mortality. For instance, the proportion of the population at risk was expected to be higher for migratory species than for territorial species. Highly fecund species were expected to better withstand (or more quickly recover from) higher mortality in comparison to those with few annual offspring.

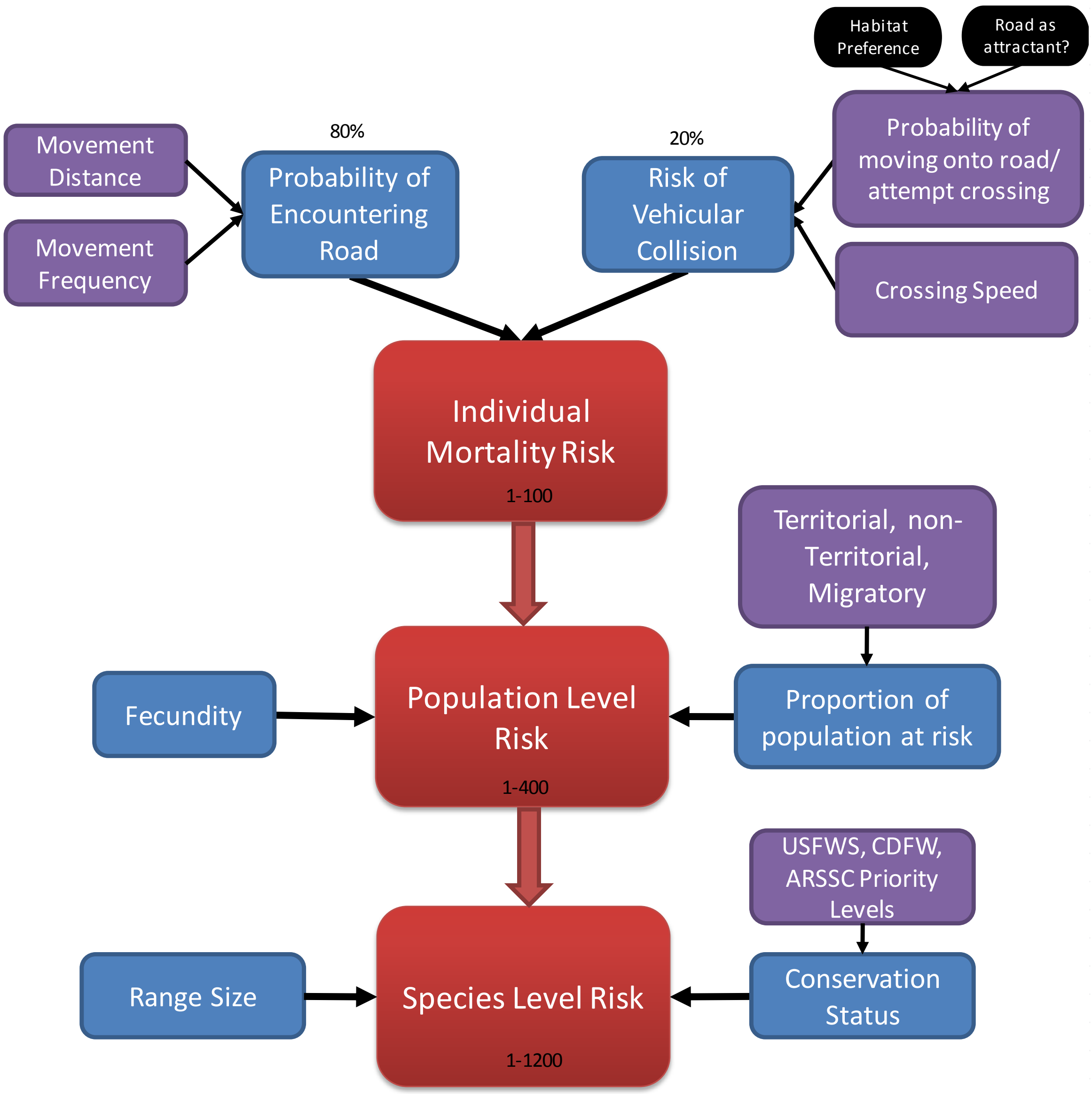

Figure 3.1. California reptile and amphibian road risk assessment conceptual model

Finally, species-level road risk was assessed by multiplying population road risk with scores for range size (both within and outside of California) and conservation status according to the U.S. Fish and Wildlife Service (USFWS 2016), the California Department of Fish and Wildlife (CDFW 2016), and California Species of Special Concern (Thompson et al. 2016). Species with smaller ranges have fewer populations and are thus less resilient to population level stressors. Endangered, threatened, and special concern species have already been designated at risk of extirpation, often due to multiple stressors, and are thus thought to be less likely to be resilient to additional road impacts.

Once all 166 species (including subspecies with conservation status) were scored for species-level road risk within both terrestrial and aquatic habitats, we took the maximum score for each species and sorted them from the highest to lowest scores. We grouped species into categories of risk (Very High, High, Medium, Low, and Very Low) based upon ranges of values that represented frequency distributions in 20% increments of all species scores

The risk assessment was done for both terrestrial and aquatic habitats to further inform mitigation. Some aquatic species may greatly benefit from fish passages while others may better benefit from terrestrial barriers and wildlife crossings or both.

Although we attempted to base the risk assessment solely upon space-use and life history characteristics, it is understood that circumstances associated with particular populations, roads, and road density may elevate or reduce the risk for certain populations and species. More details on scoring methods are found in Brehme et al., in review)

Chelonids, large bodied snakes, and toads were the highest risk groups, with 100% of chelonids, 72% of snakes, and 64% of toads at high or very high risk from roads within their terrestrial and/or aquatic habitats. Thirty-seven percent of frog species were ranked as high or very high risk, while only 18% of lizard species and 15% of salamanders were ranked at high risk from negative road impacts (Figure 2, Table 3.3).

Terrestrial and Aquatic high and very high risk species are presented in Tables 11 and 12. These results also include population level risk scores, 95% population buffer distances, confidence levels, and identification of any surrogate species used for the distance calculations.

The results are consistent with available road ecology literature in identifying known high risk species as well as calling attention to high risk species that were not previously identified. See Brehme et al. (in review) for a fuller discussion. The results will help to inform transportation planning as well as mitigation considerations for California herpetofauna by highlighting species that may require priority consideration for aquatic and terrestrial road mitigation to reduce mortality and to maintain population and species level connectivity.

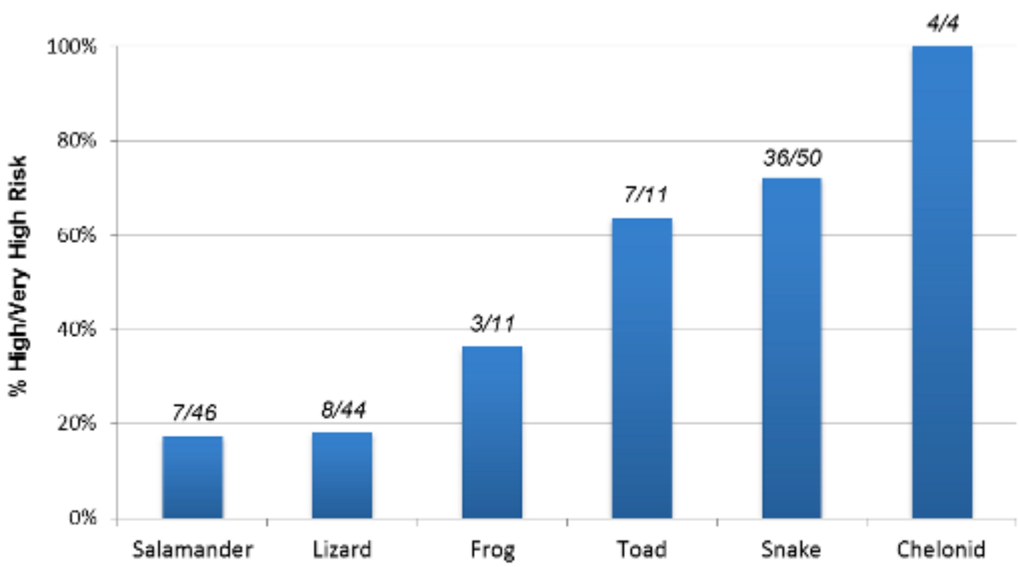

Figure 2. Percentage of High/Very High Risk taxa to total taxa in California, according to species group category.

Risk Level (Terrestrial)		Species			Risk Scores (Terrestrial)		Movement Distances (Terrestrial)		
Species	Population	Group	Common Name	Scientific name	Road Risk: Species- Level	Road Risk: Population-Level	95% Population Movement Distance (m)	Confidence in Distance Estimate	Surrogate Used
Very High	Very High	Snake	San Joaquin Coachwhip	*Masticophis flagellum ruddocki*	689	285	1618	High	
	Very High	Snake	Alameda Striped Racer	*Masticophis lateralis euryxanthus*	652	221	631	Med/High	
	Very High	Tortoise	Mohave Desert Tortoise	*Gopherus agassizii*	580	240	1155	High	
	Very High	Salamander	Red-bellied Newt	*Taricha rivularis*	561	228	1600	High	
	Very High	Snake	Baja California Coachwhip	*Masticophis fuliginosus*	534	285	1904	High	
	Very High	Snake	Coast Patch-nosed Snake	*Salvadora hexalepis virgultea*	533	221	631	Low	*M. lateralis*
	Very High	Salamander	Coast Range Newt	*Taricha torosa*	532	228	2500	Med/High	
	Very High	Lizard	Banded Gila Monster	*Heloderma suspectum cinctum*	446	210	1250	High	
	High	Salamander	California Tiger Salamander	*Ambystoma californiense*	437	152	1849	Med/High	
	Very High	Salamander	Sierra Newt	*Taricha sierrae*	437	228	2050	Med	*T. torosa, T. rivularis*
	Very High	Snake	Striped Whipsnake	*Masticophis taeniatus*	425	300	2236	Med	
	Very High	Lizard	Flat-tail Horned Lizard	*Phrynosoma mcallii*	425	217	788	Med/High	
	High	Lizard	Blunt-nosed Leopard Lizard	*Gambelia sila*	393	133	510	High	
	Very High	Snake	Panamint Rattlesnake	*Crotalus stephensi*	387	238	938	Med	*C. mitchelli*
	Very High	Snake	Baja California Ratsnake	*Bogertophis rosaliae*	387	238	842	Low	*Elaphe obsoleta*
	High	Frog	California Red-legged Frog	*Rana draytonii*	380	152	1864	High	
	High	Toad	Black Toad	*Anaxyrus exsul*	379	128	951	Low	*A. canorus, A. punctatus*
	High	Toad	Yosemite Toad	*Anaxyrus canorus*	379	128	1152	Med/High	
	High	Lizard	Cope's Leopard Lizard	*Gambelia copeii*	372	175	643	Low/Med	*G. wislenzii*
	High	Toad	Sonoran Desert Toad	*Incilius alvarius (Possibly extinct in CA)*	361	152	1400	Low/Med	*A. cognatus*
	Very High	Lizard	Desert Horned Lizard	*Phrynosoma platyrhinos*	356	259	1300	Med/High	
	High	Snake	California Glossy Snake	*Arizona elegans occidentalis*	340	154	316	Low	*R. lecontii*
	Very High	Snake	Racer	*Coluber constrictor*	334	308	1800	Med	
	Very High	Snake	Coachwhip	*Masticophis flagellum*	333	285	1618	High	
	High	Toad	Arroyo Toad	*Anaxyrus californicus*	331	128	1082	Med/High	
High	Very High	Snake	Striped Racer	*Masticophis lateralis*	322	221	631	Med	
	High	Snake	Red Diamond Rattlesnake	*Crotalus ruber*	321	175	853	High	
	Very High	Snake	Speckled Rattlesnake	*Crotalus mitchellii*	317	238	938	High	
	Med	Salamander	Santa Cruz Long-toed Salamander	*Ambystoma macrodactylum croceum*	308	104	800	High	
	Very High	Salamander	Rough-skinned Newt	*Taricha granulosa*	304	228	2050	Med	*T. torosa, T. rivularis*
	High	Snake	Regal Ring-necked Snake	*Diadophis punctatus regalis*	298	152	566	Low/Med	
	High	Snake	California Lyresnake	*Trimorphodon lyrophanes*	293	195	800	Low	
	High	Frog	Northern Red-legged Frog	*Rana aurora*	291	152	1864	Med	*R. draytonii*
	High	Turtle	Southwestern Pond Turtle	*Actinemys marmorata (pallida)*	283	128	448	High	
	Very High	Snake	Western Patch-nosed Snake	*Salvadora hexalepis*	276	221	631	Low	*M. lateralis*
	High	Snake	Mojave Rattlesnake	*Crotalus scutulatus*	276	189	815	Med/High	
	High	Snake	Sidewinder	*Crotalus cerastes*	263	186	767	High	
	High	Snake	Sonoran Lyresnake	*Trimorphodon lambda*	260	195	800	Low	
	Med	Salamander	California Giant Salamander	*Dicamptodon ensatus*	260	120	600	Low	*D. tenebrosus*
	Very High	Snake	California Mountain Kingsnake	*Lampropeltis zonata*	254	203	694	Low/Med	*L. getula*
	Very High	Snake	Western Rattlesnake	*Crotalus oreganus*	250	231	1096	Med/High	
	High	Snake	Desert Nightsnake	*Hypsiglena chlorophaea*	241	175	566	Low	*D. punctatus*
	Med	Lizard	Switak's Banded Gecko	*Coleonyx switaki*	236	90	200	Low	*C. variegatus (AZ)*
	Med	Toad	Western Spadefoot	*Spea hammondii*	234	104	670	Med	
	High	Snake	Coast Nightsnake	*Hypsiglena ochrorhyncha*	233	175	566	Low	*D. punctatus*
	Very High	Snake	California Kingsnake	*Lampropeltis californiae*	231	231	694	Low/Med	
	High	Lizard	Long-nosed Leopard Lizard	*Gambelia wislizenii*	226	175	643	Med/High	
	High	Toad	Great Plains Toad	*Anaxyrus cognatus*	222	152	1400	Med/High	
	High	Toad	Woodhouse's Toad	*Anaxyrus woodhousii*	222	152	1400	Low	*A. cognatus*
	Med	Lizard	Coastal Whiptail	*Aspidoscelis tigris stejnegeri*	219	105	300	Low	*A. hyperythra (X2 for body size)*
	High	Snake	Western Shovel-nosed Snake	*Chionactis occipitalis*	218	154	400	Low	
	High	Snake	Spotted Leaf-nosed Snake	*Phyllorhynchus decurtatus*	218	154	400	Low	*C. occipitalis*

Table 3.3. Amphibian and Reptile Road Risk Assessment (Terrestrial Habitat): Very High Risk Species (80-100% Percentile) and High Risk Species (60-80% Percentile)

Risk Level (Aquatic)		Species			Risk Scores (Aquatic)		Movement Distances (Aquatic)		
Species	Population	Group	Common Name	Scientific name	Road Risk: Species- Level	Road Risk: Population-Level	95% Population Movement Distance (m)	Confidence in Distance Estimate	Surrogate Used
Very High	Very High	Snake	Giant Gartersnake	*Thamnophis gigas*	710	240	1556	High	
	Very High	Turtle	Southwestern Pond Turtle	*Actinemys marmorata (pallida)*	707	320	3145	High	
	Very High	Snake	San Fransisco Gartersnake	*Thamnophis sirtalis tetraaena*	663	224	1146	Med	*T. sirtalis*
	Very High	Snake	California red-sided Gartersnake	*Thamnophis sirtalis infernalis*	588	224	1146	Low/Med	*T. sirtalis (species)*
	Very High	Turtle	Northwestern Pond Turtle	*Actinemys marmorata (marmorata)*	547	320	2130	High	
	Very High	Snake	Two-striped Gartersnake	*Thamnophis hammondii*	541	224	934	Low/Med	
	High	Turtle	Sonora Mud Turtle	*Kinosternon sonoriense*	399	168	1000	Med	
	Very High	Snake	Aquatic Gartersnake	*Thamnophis atratus*	355	224	934	Low/Med	*T.gigas (-40% for size diff)*
High	Very High	Snake	Northwestern Gartersnake	*Thamnophis ordinoides*	327	224	1075	Low	*T. hammondi*
	Med	Frog	Oregon Spotted Frog	*Rana pretiosa (Possibly extinct in CA)*	315	120	1300	Low	
	High	Snake	Sierra Gartersnake	*Thamnophis couchii*	304	192	934	Low/Med	*T.gigas (-40% for size diff)*
	Med	Frog	California Red-legged Frog	*Rana draytonii*	300	120	1864	High	
	Med	Toad	Sonoran Desert Toad	*Incilius alvarius (Possibly extinct in CA)*	285	120	1400	Low/Med	*A. cognatus*
	Med	Toad	Black Toad	*Anaxyrus exsul*	284	96	951	Low/Med	*A. canorus, A. punctatus*
	Med	Toad	Yosemite Toad	*Anaxyrus canorus*	284	96	1152	Med/High	
	High	Snake	Checkered Gartersnake	*Thamnophis marcianus*	280	192	1075	Low	*T. hammondi*
	Very High	Snake	Common Gartersnake	*Thamnophis sirtalis*	271	224	1146	Low/Med	
	Med	Toad	Arroyo Toad	*Anaxyrus californicus*	248	96	1000	Med/High	
	High	Snake	Western Terrestrial Gartersnake	*Thamnophis elegans*	240	192	934	Low/Med	*T.gigas (-40% for size diff)*
	Med	Frog	Northern Red-legged Frog	*Rana aurora*	230	120	1864	Med	*R. draytonii*

Table 3.4. Amphibian and Reptile Road Risk Assessment (Aquatic Habitat): Very High Risk Species (80-100% Percentile) and High Risk Species (60-80% Percentile)

In conjunction with the risk assessment, specific roads of concern were identified and mapped for all high risk species and this is in preparation as a part of the programme. The California Department of Transportation (Caltrans) and California Department of Fish and Wildlife (CDFW) commissioned the California Essential Habitat Connectivity Project (CEHC) that identified and mapped functional network of connected wildlands State-wide, essential to the continued support of California's diverse natural communities in the face of expanding land take for human development and climate change effects. The CEHC intended to make transportation and land-use planning more efficient and less costly, while helping reduce dangerous wildlife-vehicle collisions.

We used the CEHC map network, along with "small landscape blocks (> 1.0 km^2) that are important for small vertebrate connectivity, to identify and prioritize DOT road segments of concern for all high and very high risk reptile and amphibian species. This information will be used to inform future road planning and mitigation efforts in California such as the need for wildlife passage and barrier structures.

4. MITIGATION OF IMPACTS

Road passage/crossing categories (type) nomenclature follows that used in Langton et al. (2015). Where relevant, structures are described for their construction purpose as well as their potential use as a herpetofauna passage

4.1. Engineered (purpose-built) solutions

Type 1: Mountain tunnels and Green Bridges/Wildlife Overpasses

Description and applications

There are many examples of mountain tunnels constructed to minimise above ground environmental disturbance and construction cost, especially in alpine regions of the world. Some large 'cut and cover' road tunnels are designed to enable animal movements above a major Highway, such as at Bell Common tunnel on the M25 road near Epping, England. Wildlife overpasses have been built most frequently in Germany (over 15 built since 2009) and in the Netherlands (25 since 2004), as a part of national nature defragmentation strategies. Switzerland and Austria also have made early provision. There are several in most European countries and NAM States and Provinces with active plans for many more to be constructed. A few have been built with herpetofauna specifically in mind or as a major component. Overpasses have been built for some time for large 'game' animals and livestock transfer. Road bridges with green verges may also offer some passage opportunity across wide busy motorways and main roads.

Zone	Variation/types, location, examples	Monitoring/outcomes
a) Global	The Compton Road overpass, southern Brisbane, Queensland, Australia is used extensively by reptiles and amphibians with 19 species captured or detected on the overpass. This is over 60% of the herp species known to occur in the surrounding forest (McGregor et al. 2015). For a green bridge at Segeberg, Schleswig Holstein, Germany the target species are: snakes, amphibians, small mammals and invertebrates (e.g., bush crickets). Habitat corridors are enhanced on both sides of the road to a distance of several km (Reck et al. 2011). Netherlands has several Green Bridges including at Woeste Hoeve and Terlet, built in the late 1980s for larger mammals but were found also to be used by a range of herpetofauna. There has been further construction in the Netherlands (Creemers and Struijk 2012) principally designed for amphibians, reptiles, and mammals e.g. the Green Forest Overpass A2 motorway built in 2005 with ponds and wet ground to aid dispersal of seven species of amphibians on either side of and along the top of the bridge (van der Grift et al. 2010).	Pfister et al. (1997) recommended minimum wildlife overpass width of 50 m for wildlife in general, based on study of 16 green bridges located in France, Germany, Switzerland and the Netherlands.
b) North America	There are no known Type 1 structures built for herpetofauna in North America. Of those built for key species, usually large mammals, some are recorded as used by herpetofauna, e.g. the overpass that spans the Trans-Canada Highway in Banff, Alberta which is used by garter snakes. There are crossings in Montana, Wyoming, Arizona and Utah that may be used by herpetofauna. Washington is constructing an Interstate-90 wildlife overpass to give animals safe passage including lizards.	Data deficient
c) California	There are no known Type 1 structures for herpetofauna in California. There are proposals of green bridges for other species, such as mountain lions in the Liberty Canyon Wildlife Corridor at Agoura Hills, west of Los Angeles that may also be used by herpetofauna.	Data deficient.

Type 2: Open bridges and viaducts

Description and applications

Locations where existing larger bridges or raised road sections are built to accommodate road design, such as crossing a river or wetland provides some safe space underneath for animals to cross. These range from the smaller (120ft/36.5 m) bridges to those several hundred yards/metres long or more across valleys and canyons. These have a wildlife passage function by virtue of their larger designs that span aquatic and terrestrial habitat.

Zone	Variation/types, location, examples	Monitoring/outcomes
a) Global	There are very many locations worldwide. Bridges are often cheaper to build and to maintain than winding roads on slopes and use less land. They are often essential as river and stream crossings and where land is permanently or seasonally flooded.	There is little data from studies on herpetofauna compared for example with fish, but the assumption is that all species will be expected to pass under these larger raised structures if they span the habitat that the species occupy
b) North America	There are probably thousands of such structures in larger States. No specific studies of use by herpetofauna appear to have been undertaken.	As Above
c) California	There are probably thousands of such structures in California. No specific studies of use by herpetofauna appear to have been undertaken.	As above

Type 3: Smaller road underpasses under 60ft/20m

Description and applications

These include the smaller (10-60ft/3.0-18.0 m), typically 30 ft/9.0 m wide concrete box bridge structures that accommodate both permanent streams and the intensive, short period seasonal flooding in otherwise more arid lands. Some are used for pedestrian, maintenance or agricultural access. There are many instances of their use as wildlife passages, sometimes with herpetofauna in mind. As a part of this project and in consultation with Caltrans, it will be useful to generate a checklist of different types of structures, frequency of occurrence and general characteristics to develop a sampling profile with respect to use by amphibians and reptiles. Some of the small Type 3 passages have been purpose-built for herpetofauna and these are usually under 6 m wide.

Zone	Variation/types, location, examples	Monitoring/outcomes
a) Global	There are millions of locations worldwide and although mainly designed for water management, many remain dry for months or even years. Because there is typically no fencing leading animals to these underpasses, the chance of use may be low other than for riparian species. As with Type 2 structures the walls, roofs and floor are sometimes occupied by a wide range of fauna and flora.	There appear to have been few specific studies of use of these structures by herpetofauna.
b) North America	There are probably hundreds of thousands of such structures in North America, mainly designed for water management. As above	As above.
c) California	There are probably thousands of such structures in California, mainly designed for water management. As above	As above.

Figure 4.1. Small engineered Type 3 passage across a 2-lane road in a heathland area in The Netherlands. The passage is dual-purpose, designed for use for livestock (sheep) movements and the fenced-off area is filled with tree branches that provide cover for wildlife including small lizards and snake species.

Type 4: Culverts under 10 ft/3.0 m

Description and applications

Smaller drainage or wildlife culvert/tunnel underpasses that are over 3.3. ft/1.0 m span but under 10 ft/3.0 m diameter have often been adapted as wildlife passages, including for amphibians and reptiles.. Some are permanently flooded and 'balance' water levels either side of a road, most are seasonal and prevent water build-up, waterlogging and flooding. It would be useful to generate a list of different types of structure, frequency of occurrence and general characteristics, to develop a sampling profile for further study.

Zone	Variation/types, location, examples	Monitoring/outcomes
a) Global	Under the 12 million miles/18 million km of paved roads worldwide and probably greater length on unpaved roads, there are an estimated tens of millions or more of water drainage pipes under roads, often connecting with slopes, ditches and wetland features.	A number of such culverts have been used in amphibian and reptile passage constructions. There are a few specific studies of use of these structures by herpetofauna.
b) North America	Hundreds of thousands of water drainage pipes under roads usually connecting with ditches and other wetland features.	As above.
c) California	Many thousands of water drainage pipes under roads usually connecting with ditches and other wetland features.	As above

Figure 4.2 and 4.3. New specially designed under-road culvert at SR-58 California (Hinkley Highway re-alignment) under construction. This may well be of value as a tortoise passage.

Type 5: Micro underpasses < 3.0ft/0.9 m diameter/span

Description and applications

Micro-tunnels (under 3 ft/0.9 m span) are normally associated with natural stream accommodation and may have a road drainage function. They are constructed as passages for amphibians and reptiles with or without surface slots, according to road design and target species requirements. Because of their small size, standard plastic, metal and cast concrete structures must be deeply buried under roads to avoid collapse from the weight of vehicles. The exception is surface tunnels made from polymer concrete, which is more durable and designed to accommodate much higher loads than standard cement. Metal grating may also be strong enough but use is limited due to safety concerns, to higher speed roads.

Zone	Variation/types, location, examples	Monitoring/outcomes
a) Global	There are up to 15,000 passages in Europe within perhaps 6000 system locations.	Many anecdotal reports and brief references but quantitative studies distinctly lacking. There may be hidden grey-literature references in different languages.
b) North America	There are probably around 150 passages at around 50 system locations. Polymer concrete surface tunnels and round metal and concrete culverts represent most of the constructions.	Only a few thorough monitoring exercises have been done.
c) California	Langton et al. 2015 recorded at least 38 passages at 8 amphibian road mitigation system locations in California both public and private property not related to State Highway System for the following species; Western toad, California tiger salamander and Santa Cruz long-toed salamander. Passages for tortoises seem poorly represented in the literature. Passages built using water drainage materials and purpose-made small animal passages have been used for probably a number of projects since the 1960s, most for mammals, with up to an estimated 20 for herpetofauna, with a current installation completion rate of around one or two per year, of which around one is for herpetofauna.	System failure and lack of monitoring is highly apparent.

Figure 4.4. A purpose built multiple surface-tunnel system at Ventana Way, Seascape Uplands, Santa Cruz for the Santa Cruz long-toed salamander. This system uses mostly ACO Polymer Products purpose-made 500 mm slotted surface tunnel. Short wing walls were used and then passage passes under the pavement.

Figure 4.5. Three surface tunnels with a combination of mesh and ACO plastic panel fencing at Junipero Serra Boulevard, Stanford Hills near Lake Lagunita, constructed for California tiger salamander crossing. The light grey lines across the road show the passage positions.

Figure 4.6. Twelve Type 5 surface tunnels constructed along Wilfred Avenue, Graton resort and Casino, Rohnert Park, Santa Rosa in 2014 for California tiger salamander. The low barrier mesh fence is overgrown with grass.

Barriers: Fence and Wall Structures

<u>Description and applications</u>

Zone	Variation/types, location, examples	Monitoring/outcomes
a) Global	There are up to 15,000 passages in Europe used by herpetofauna within perhaps 6000 system locations, most but not all with barriers on one or both sides and to varying distances either side of the passages.	Many anecdotal reports & brief references but detailed studies are lacking. There may be un-located grey-literature references.
b) North America	There are probably around 200 passages at around 50 system locations. Concrete walls, metal and plastic mesh and plastic sheeting and panels are the most frequently used in barrier construction.	Only a few thorough monitoring exercises on barrier effectiveness have been completed.

c) California	Langton et al. (2015) recorded at least 38 passages at 8 amphibian mitigation systems locations in California for the following species; western toad, California tiger salamander and Santa Cruz long-toed salamander. There is extensive tortoise fencing along roads and highways in the Sonoran and Mojave deserts.	System failure and lack of monitoring is highly apparent and the role of ineffective positioning of barriers is suspected.

Scuppers

Vertical concrete barriers, standing 3.2 ft/1.0 m high or more are placed on the median in order to separate traffic moving in opposite directions and particularly where lane widths are limited on high-speed roads (FHWA 2006). These may have gaps at ground level called 'scuppers' to allow drainage or for lifting purposes that may also enable small animal permeability. Use of concrete as opposed to solid metal and or steel cable to divide a road varies according to a range of factors. Solid barriers in the median may be fixed in place or be free standing. They may also be placed at the side of roads as a temporary safety measures including as falling 'rock-stops' alongside eroding cliffs and slopes. Generally, roads that require solid dividing barriers due to high volume and speed without scuppers are likely to preclude movements of most herpetofauna species via risk of mortality but otherwise, for example in quieter period such as during the middle of the night, they may also exert a total barrier effect locally for some amphibian and reptile species by blocking movement.

Zone	Variation/types	Monitoring/outcomes
a) Global	A wide range of concrete walls and barriers have been used to separate traffic for safety reasons and these may negatively impact individuals and populations of less mobile wildlife species. Availability and use by wildlife of scuppers appears almost unstudied.	No data on herpetofauna has been located.
b) North America	Median barriers placed for mile after mile without breaks, may create a significant barrier to wildlife (Clevenger and Kociolek 2006). Most notably larger mammals may get trapped one side and hit by vehicles as a result of being held on the fast lane. The same applies to smaller vertebrates. Some central road barriers on American highways have a staggered overlap in order to allow crossing by animals that are less able to jump. Availability and use by wildlife of scuppers appears almost unstudied.	No data on herpetofauna has been located.

c) California	Some median barriers have two scuppers at the base for lifting purposes. These may allow movement of smaller species. , There have been projects in District 5 (Central Coast, San Luis Obispo) along Highway 101 and 1. These included small wildlife passage/scupper standard plan as impact minimization and mitigation measures for reptiles, amphibians and other small and medium sized species. Little data is available on their use and effectiveness at reducing mortality at present.	No data on herpetofauna has been located.

Considering there are numerous amphibian and reptile passages and barriers throughout the world, few have had details published regarding their design criteria, nor monitoring to adequately evaluate their effectiveness. Equally use of existing natural habitat 'gaps' in highways created by bridges, culverts and road tunnels under the ground has not been described or evaluated for their contribution in helping to maintain genetic and population connectivity for herpetofauna across roads.

Therefore, going forward there is both a need for properly designed studies to evaluate the effectiveness of passages and barriers, as well as conducting studies (controlled experimental or field settings) to directly test and compare the effectiveness of passage and barrier designs for maintaining species movement and population connectivity. This would help to fill the clear gap in evidence and help to solve the lack of a clear hierarchy of approaches to specifying crossings to accommodate herpetofauna, including for multi-species situations where an entire community requires connectivity.

Figure 4.7. Scupper along median barrier wall on Highway 101 near San Luis Obispo, California.

4.2. Non-engineered solutions and retrofits

Passages not intentionally constructed or designed for wildlife passage.

Type 1: Mountain tunnels and green bridges/wildlife overpasses

In theory non-engineered road bridges may be used by wildlife including herpetofauna. However, as these are designed for traffic, use by wildlife is if it occurs at all, limited to quiet traffic periods and use more by large vertebrates that can move quickly over several hundred metres at a time as opposed to the slower-moving amphibians and reptiles, although evidence of this is lacking.

Zone	Variation/types,	Monitoring/outcomes
a) Global	Many road bridges exist to allow vehicles to cross larger high speed roads, often at junctions. These may be used by wildlife including herpetofauna especially at night in rural areas. Some may have paved walkways for pedestrians or 'green verges' on the bridge that makes the use of them by animals less hazardous for some species. Some may be built to allow 'game' passage for hunted species.	There are many thousands of mountain tunnels worldwide especially in montane landscapes. Tens of thousands of (non-green) bridges, nearly all built for vehicle traffic and not wildlife use. Studies for herpetofauna are few. There is one comprehensive study for amphibians. See this study.
b) North America	There are several hundred road tunnels in North America. Some States have only a few while others 30 or more. The longest tunnel is reported to be the 2.5 mile long Whittier Tunnel in Alaska. Wildlife including herpetofauna may cross main road overbridges in rural areas.	Use not documented for herpetofauna
c) California	California has around 50 road and rail tunnels and many thousands of main road vehicle junction crossings	Use not documented for herpetofauna

Type 2: Open bridges and viaducts up to 120 ft/36.5 m

Figure 4.8. A 120 ft/36.5 m Type 2 passage example. The river bridge at the junction of Campo Road with Honey Springs Road and Otay Lakes road, San Diego County. Although some amphibians and reptiles pass underneath, this is an example where a retrofit of barrier at each end on both sides could bring about a significant reduction in mortality of herpetofauna.

Zone	**Variation/types,**	**Monitoring/outcomes**
a) Global	Open bridges and viaducts made from concrete, steel and sometimes stone and wood are commonplace and may span urban, agricultural and more undisturbed landscapes, especially steep valleys and water courses. Some span many miles on stilts while others are built where the gap is too big for culverts. Traditionally these have not been assessed for wildlife including herpetofauna, probably because of the assumption that wild animals travel freely underneath them. In some cases roads built over marshes can be raised up on stilts during re-building to help wetland recovery (Scoccianti 2008). Some narrow bridges are designed for livestock and pedestrian movement.	Use not documented for herpetofauna
b) North America	As above, there are probably tens of thousands of open bridges and viaducts in North America. Roads allowing water flow under them may occur on wetland routes, such as those crossing the Everglades habitats in Florida.	Little or no documentation for herpetofauna

c) California	As above, there are probably thousands of open bridges and viaducts in California. Herpetofauna mortality hotspots are anecdotally linked strongly with locations where rivers and streams cross under roads.	Little or no documentation for herpetofauna use

Type 3: Smaller road underpasses under 60 ft/20 m

Figure 4.9. A 30ft/10 m, Type 3 example of a three-span concrete bridge along Campo Road Route 94 that is situated around ½ mile south of Jamul, San Diego County.

Zone	Variation/types,	Monitoring/outcomes
a) Global	There are possibly millions of small span bridges and culverts over small streams, seasonal flash-flood routes and other water bodies that may be used as wildlife corridors, including herpetofauna.	Little or no documentation for herpetofauna use.
b) North America	There are possibly hundreds of thousands of small span bridges and culverts over small streams or seasonal flash-flood routes and other water bodies that may be used as wildlife corridors, including herpetofauna.	Little or no documentation for herpetofauna use.

c) California	There are thousands of small span bridges and culverts over small streams or seasonal flash-flood routes and other water bodies that may be used as wildlife corridors, including herpetofauna.	Little or no documentation for herpetofauna use.

Type 4: Culverts under 10 ft/3.0 m

Zone	Variation/types,	Monitoring/outcomes
a) Global	There are possibly many millions of water culverts of this size over streams and ditches that may be used as wildlife movements, including herpetofauna. Ledges and walkways can be retrofitted to the sides of stream/river culverts to make dry platforms for animals to cross under roads.	Little or no documentation for herpetofauna use, mainly for mammals.
b) North America	There are possibly tens of thousands of water culverts of this size over streamlets that may be used as wildlife corridors, including herpetofauna. Ledges and walkways can be retrofitted to the sides of stream/river culverts to make platforms for animals to use.	Little or no documentation for herpetofauna use, mainly for mammals.
c) California	There are possibly thousands of water culverts of this size over streamlets and ditches, which may be used as wildlife corridors, including herpetofauna. Ledges and walkways can be retrofitted to the sides of stream/river culverts to make platforms for animals to use.	Little or no documentation for herpetofauna use, mainly for mammals.

Type 5: Micro underpasses <3.3ft/1.0 m diameter/span

Zone	Variation/types, location, examples	Monitoring/outcomes
a) Global	There are estimated tens of millions of small culverts underneath roads around the world placed for drainage purposes. Passages built using water drainage materials and purpose-made small animal passages have been used for probably around 8,000-12,000 projects since the 1960s, mostly for mammals and amphibians, with a current installation rate of around 300 systems/1000 passages per year	Generally little historic information other than for around 10 countries. See this study

b) North America	There are millions of small culverts underneath roads across North America, placed for drainage purposes. Passages built using water drainage materials and purpose-made small animal passages have been used for probably around 500 projects since the 1960s, almost all for mammals with around 30 for herpetofauna, with a current installation rate of around 10 systems per year of which around 2 are for herpetofauna,	Generally little information other than for a few States/Provinces. See this study
c) California	There are tens of thousands or more small culverts underneath roads across California, placed for drainage purposes.	Generally little information is readily available other than for a few bespoke amphibians systems (Langton et al. 2015).

4.3. Construction design and materials

The most comprehensive review for herpetofauna is Iuell et al. (2003) the 'COST 341 review for Europe; Habitat Fragmentation due to Transportation Infrastructure. Clevenger & Huijser (2011) Wildlife Crossing Structure Handbook, Design and Evaluation in North America provides some additional information.

Type 1: Mountain tunnels and Green Bridges/Wildlife Overpasses

Zone	Variation/types
a) Global	Mountain tunnels are usually within drilled rock. Wildlife overpasses are made from corrugated steel plate, concrete and sometimes from heavy timber lattice (e.g. a pilot project in Germany between Berlin and South Brandenburg, built in 2012). Layers of geotextile and aggregates are used to form moisture protection for the structure, to enable drainage of excess water to prevent waterlogging and to minimise structural degradation. The upper sides of the overpass are fenced from ground level to a height of 2.0 m or more. Surfaces are covered with up to 3.3ft/1.0 m of soil and planted with vegetation and may have rocks, logs and water features place on them. The general view is that these structures should be as wide as possible and 50 m wide should be considered as a minimum ideal width.

b) North America	As above. Data on North American wildlife overpasses has not been collated, but it is not known that timber constructions have been used in North America.
c) California	There are no known wildlife overpasses built in California.

Type 2: Open bridges and viaducts

Zone	Variation/types
a) Global	Mostly concrete, steel and wood constructions with and without (single span) pillars.
b) North America	As above.
c) California	As above.

Type 3: Smaller road underpasses under 66 ft/20 m

Zone	Variation/types
a) Global	Mostly concrete, rock, brick, steel and wood constructions. May be rectangular, square, half round or half/semi-elliptical in cross section. May be placed singly (usually) or in series. Ground underneath may be bare or vegetated according to size and length. May have additional materials; trees, log stacks, boulders to aid some species use. May have ditch or stream within them and sometimes designed for flood conditions. Aquatic tunnels may have shore area or ledges for pedestrian and wildlife use. May have vehicular access and livestock movement shared-purpose.
b) North America	As above
c) California	As above

Type 4: Water culverts under 10 ft/3.0 m

Zone	Variation/types
a) Global	Mostly concrete, rock, brick, steel and wood constructions. Mostly rectangular, square, half round or half/semi-eliptical in cross section. May be placed singly (usually) or in series. Ground underneath usually bare due to size and length. May have ditch or stream within them and sometimes designed for flood conditions. Aquatic tunnels may have shore area or ledges wildlife use.
b) North America	As above
c) California	As above

Type 5: Micro underpasses < 3.3 ft/1.0 m diameter/span

Zone	Variation/types
a) Global	Mostly concrete, polymer concrete and steel construction. Mostly rectangular, arched, round, half or three quarter round in cross section. Typical 10-20 m or more long according to road and embankment width/ road lane numbers. May be placed singly or in series and usually but not always with barrier guide wall and fencing types. Either bare (polymer concrete) or with soil.
b) North America	As above
c) California	As above

Figure 4.10. One of thousands of degrading cross-road corrugated steel drainage culverts on a Californian road, soon to be in need of refurbishment. Such future structures can be adapted to serve as valuable wildlife passages as well as for water drainage purposes.

Barriers

Zone	Variation/types
a) Global b) North America c) California	Sometimes built in association with a taller deer or livestock fence. Usually 500 mm high plus or minus 200 mm, with around 200 mm in addition underground to prevent under-digging. Most barriers have overhangs to reduce over-climbing. **Guide walls** Guide walls are solid permanent structures that may also have a soil/slope retention purpose. Made from steel, concrete or polymer concrete they are built into the road embankment as an integral part of the road structure. **Fencing** Thin polythene/geotextile/plastic material including shade cloth may be used for temporary applications but lacks strength and durability. Formed (extruded) plastic (polypropylene/polyethylene) sheeting, 1, 2 or 3 mm thick is commonly used, fixed vertically or at an angle on wood, plastic or metal posts. Thicker injection-molded plastic curved panels are also used with plastic, recycled plastic, wood or steel support posts. Lifespan expectation is 10-25 years plus. Galvanised (zinc coated) steel or other steel alloys designed for rust-proofing is used for more permanent barriers, as is polymer (resin) concrete. Lifespan expectation is generally 40-100 years plus. Steel mesh with fine holes is sometimes coloured brown to help blend into the landscape and may be most suitable in harsh desert/exposed environments. Here, solid materials may catch soil-blow and become buried and plastics may distort through expansion warping or degrade due to high Ultra Violet light exposure.

Figure 4.11. Two kinds of reptile (small snakes and lizards) guide walls at a single lane with cycle path Type 5 passage location in The Netherlands. One (left hand side) is molded plastic and the other (right hand side) is polymer concrete. Then guide walls are approximately 500 mm tall.

A number of companies manufacturing purpose-made wildlife passage and barrier materials specifically aimed at herpetofauna are shown below.

Table 3.4. Companies manufacturing wildlife passage and barrier materials specifically aimed at herpetofauna.

Name	Headquarters Areas covered	Web link to information
ACO	Germany Worldwide	http://www.aco-wildlife.com/home/
Animex	Worldwide UK	https://animexfencing.com/
Ertec Environmental Systems	Sacramento USA	http://ertecsystems.com/Products/Wildlife-Exclusion-Fence---Special-Status-Species-Protection
Maibach Vul GmbH	Germany Europe	https://www.maibach.com/amphibienschutz.html
Volkmann and Rossbach GmbH	Germany Europe	http://www.amphibienschutz.de/zaunhersteller/volkmann/volkmann.htm

4.4. Construction design and materials; information and gaps

There are a number of publications in European languages concerning construction of different wildlife passage types. Manuals and other material from Germany (x3), France (x2), Poland, Croatia, Sweden and Switzerland (all x1) have been examined in addition to that in the English language outside North America (including Australia and Tazmania). Much of the European information was summarised in COST 341, a handbook for 'identifying conflicts and designing solutions' (Iuell et al. 2003). This is a relevant reference volume for North America and is currently being reassessed for updating by European Road Authorities.

Standard road structure constructions in North America are defined in the American Association of State Highway and Transportation Officials (AASHTO) volumes where many are also illustrated. Some of these structures relate to environmental protection and most address their main road transportation functions only. The BMP section of this report describes the literature published more recently specifically describing wildlife passages.

The FHWA Wildlife Crossings Structure Handbook (Clevenger and Huijser 2011) refers particularly to wildlife design needs and the better functioning of passages. It does not evaluate construction materials.

The BMP for herpetofauna in Ontario (OMNRF 2015) provides much information on structure types, materials and dimensions for different species and compliments information within the two 2015 road ecology overview book volumes (Andrews et al. 2015, Van der Ree et al. 2015).

A collection of roughly 15 publications, some in English and some in European languages, now allows for fuller coverage of passage structure construction variables, from major structure materials to fine tuning of retro-fit river culvert shelf dimensions, enabling a more detailed approach that may be habitat and species specific. These may also be usefully brought together in the 'hot sheet' format for practitioner reference.

Major gaps that appear in reviewing construction materials include;

- There have been attempts to document minimum passage type/size to maximise passage use, but not in relation to fulfilment of clear system objectives. Passage type/size would benefit from discussion and clear choice options for construction and construction materials for system designers, in respect of the proportion of a population required to move through passages in each direction over time.

- Clear indications of the durability and lifespan of various barrier construction materials is needed. This should be described according to composition, thickness and exposure to environmental degradation from expansion and contraction, sunlight and road-environment chemicals.

- An almost total lack of information on the extent of use by herpetofauna of existing road culvert and bridge structures that are not specifically engineered for wildlife purposes. It is not know the extent to which existing structures are used by herpetofauna including existing wildlife crossing structures built for larger animals. For larger structures this may relate to broad assumptions that they either are or are not used. Camera technology and standard methods makes assessing this far easier and cheaper than in the past. Information on smaller culverts would be particularly useful (Types 3-5).

Figure 4.12. Some types of cast plastic barriers may expand and contract in heat and sunlight causing problems for joinings that do not allow for such movements.

5. MONITORING AND PERFORMANCE EVALUATIONS

5.1. Review summary

There are a number of road impact mitigation techniques that have been employed over the past decades to reduce mortality of amphibians and reptiles on roads (Andrews et al. 2006, Beebee 2013, Ontario Ministry of Natural Resources and Forestry 2016). Many European projects have focused on reducing road-kills of amphibians, primarily toads, frogs, salamanders and newts with a few reptile or herpetofauna community designs only. In North America, efforts have been directed at a richer and more diverse range of amphibian and reptile species, but mainly on salamanders and freshwater turtles. In both areas investigations and test projects for new species are increasing. In the last 20 years, the concern and agency interest or requirement to mitigate road impacts of amphibians and reptiles has grown worldwide, as has the number of passage and barrier installations and studies.

We identified 75 sources of information in our search for technical reports and peer-reviewed articles in the English language (December 2016) that focused on monitoring and performance evaluations of passage and barrier constructions for amphibian and reptile populations. The list of studies captured the majority of accessible reports appearing in international journals, conference proceedings, and a proportion of government/consultant technical reports. Features of the studies examined were grouped into 4 main areas: 1) Geography/taxa: Where studies were conducted and on what taxa; 2) Mitigation: Type of infrastructure evaluated; 3) Research/Monitoring: Study design, variables evaluated, and 4) Recommendations/Peer Review.

Of the 75 sources, 23 were excluded from our summary and review on the grounds that they reported on herpetofauna generally and were not species-specific, or were reviews and not original study-based articles or duplicative of studies in our search. We used the remaining 52 sources to assess the state of the research and identify knowledge gaps. There were some issues in summarizing the data presented in the documents within the information columns we designed, as some studies were less transparent in describing methods, study design, baseline species information and results. For that reason summary information was not possible from all of the sources we evaluated. Since the 52 sources were identified a few further publications have been located and the wider project will continue to gather relevant information.

We summarized 52 studies evaluating mitigation measures for amphibians and reptiles (Table 5.1.). Studies have been carried out on all continents but Antarctica (Europe, Australia/Oceania, North America, South America, Africa and Asia). The majority of studies we reviewed were from North America (63%, n=33) and Europe (21%, n=11). Few studies were conducted in Australia/Oceania (n=6), South America (n=1) and Africa (n=1). Note that this sample does not include several studies in European languages, principally German, Dutch, French and Spanish, however many of these were examined to some extent looking for any particularly important outcomes.

Of the North American studies, 23 were conducted in the United States (US), while 10 were conducted in Canada. European studies were dispersed near equally in number among many countries. Studies from the US were largely from California and New York State (n= 5 and 4, respectively). Canadian studies were primarily from Ontario (n=6), followed by Alberta and British Columbia (n=2 each). The representation of studies in our search may be slightly biased in our efforts to search for studies conducted in California or on California species elsewhere in North America.

Regarding taxa, the large majority were multiple species evaluations. Of the 52 studies, California taxa (California species or similar sub-species or races with ranges beyond the State) comprised 27% (n=14) of the review material. Only 10 North American species were the focus of single-species research and monitoring – California taxa shown in bold: dunes sagebrush lizard, **flat-tailed horned lizard**, **desert tortoise, Santa Cruz long-toed salamander, long-toed salamander, California tiger salamander**, spotted salamander, **western toad**, eastern box turtle, and Blanding's turtle.

Overall, we found the greatest amount of information for frogs, salamanders & newts, followed by turtles, toads and snakes. Effectiveness of passages and barrier systems for lizards and tortoises were the least studied. These trends reflect a number of factors. Frogs are relatively ubiquitous and turn up in many studies where they are not the main focus. Salamanders and newts appear to have been well studied due to mitigation brought on by legal protection. Lizards are small, less visible on roadways, and relatively few species are listed or have legal protection. Tortoises are often present in low density and in restricted desert habitats, however they are highly protected and vulnerable and it is generally surprising how little published information is available. However, there are many ongoing radio-telemetry studies that likely have high value information with regard to the effectiveness of barrier fencing and underpasses for these species.

One of the problems of studying seven species groups and five categories of crossings (35 sub-categories) is that there were rarely more than a few species with more than two or three studies for the same type of crossing system, so the information is widely and lightly spread. Several studies included multiple species but most were single species studies. Single species study was often generated due to legal requirements to mitigate protected species and that drove the objectives of the mitigation and study. Effect of passages on non-target species was rarely taken into account in any detail.

Population size and distribution data for study sites was almost always low, particularly before and after installation. Determination of population trends ranged from amphibians with a generation time of around a year, to tortoises taking a decade or longer to reach sexual maturity.

Few studies defined success criteria, performance goals or metrics. In most there is an implicit understanding that the aim or wish is to get as many individuals as possible out through and returning back via the passage system over a time period according to the target species needs. Yet this was rarely commented upon other than mention of the numbers of animals using the passage (for part or full crossings) during the study period. There is a general reference to mitigation being defined in terms of reducing mortality of animals on the road(s) in question and success being judged only in terms of reduced road mortality from barrier construction as opposed to passage use levels. Almost no mitigation studies referred to targets for population-level or genetic connectivity. In no instances were acceptable passage use levels pre-determined and success or failure criteria mentioned. This was surprising as a number of projects were protected species mitigation where such outcomes determine design criteria. Despite the fact that many studies were not designed to test specific attributes of the mitigation measures, 92% of them provided recommendations for future design and implementation of mitigation for herpetofauna.

Rarely was long-term mark and recapture used to monitor the activity patterns of individuals. This appears mostly, for in-situ studies, to relate to the lack of pre-construction population studies and the lack of detailed rationales for the intended outcome of the mitigation. Cost restrictions, and perhaps a reluctance to describe failure thresholds were also considered likely to play a role.

Most studies emphasized the extent of use of or behaviour towards passages and barrier encounters. There were few studies of adaptive improvements to crossing systems such as fine tuning or reconstruction of under-performing or failed systems, This relates also to system repair and maintenance once built ((Creemers and Struijk 2012).

The duration of studies was highly variable, ranging typically from a few months to 3 years with most studies under 24 months. Often research was a sample from annual movements and confined to a few months per year because seasonal movement periods are often short-lived and the process is almost always time consuming and cost-limited. This limits the certainty over use-levels overall and some studies have shown that movement patterns may be less predictable than generally supposed. The length of studies are often related to road-project lifespans that tend to hand over the project from the road constructor to the road maintenance authority with little provision for study continuity from the pre-construction phase through to any long-term, post-construction monitoring period and long term maintenance commitment.

Table 5.1. Summary of source information used in literature review. Sources with studies in California are in grey shade.

Source	**Country**	**Taxa[1]**	**Species[2]**	**Passage/ Barrier/ System used**	**Passage/ Barrier/ System use Level[3]**	**System Evaluation[4]**
Allaback and Laabs 2002	USA	SA	Santa Cruz long-toed salamander	Yes	Low	Low/no use
Aresco, 2005	USA	Tu	Multi	Yes	High	Used
Ascensao and Mira 2007	Portugal	L, TS	Multi	Yes	Low	Undet
Bager and Fontoura 2013	Brazil	L, TS, Tu	Multi	Yes	Low	Undet
Bain 2014	USA	SA	Calif tiger Salamander	Yes	High	Used
Baxter-Gilbert et al. 2015	Canada	L, SA, Tu	Multi	Yes	Low	Low/no use
Baxter-Gilbert et al. 2013	Canada	Tu	Multi	Yes	Low	Low/no use
Bellis et al. 2013	USA	F, TS, Tu	Multi	NR	NR	Undet
Boarman and Sazaki 1996	USA	To	Desert tortoise	Yes	High	Used
Brehm 1989	Germany	F, SA, TS	Multi	Yes	Low	Undet
Caverhill et al. 2011	Canada	Tu	Snapping turtle Blanding's turtle	Yes	Low	Used
Chambers and Bencini 2015	Australia	L, TS	Bobtail lizard Other lizards Dugite	Yes	Low	Undet
Cunnington et al. 2014	Canada	F, T	Multi	Yes	High	Used
Dodd et al. 2004	USA	AS, F, L, T, TS, Tu	Multiple	Yes	High	Used
Dulisse and Boulanger 2013	Canada	T	Western toad	Yes	Low	Low/no use
Eads 2013	USA	TS	Ribbon snake Garter snake	Yes	High	Used

Fitzsimmons and Breisch 2015	USA	F, SA	Multi	Yes	NR	Undet
Grandmaison 2011	USA	L	Multi	Yes	High	Undet
Gunson 2015	Canada	AS, F TS, Tu	Multi	No	No use	Low/no use
Gunson 2017	Canada	Tu	Snapping turtle Blanding's turtle	Yes	Low	Undet
Guyot and Clobert 1997	France	To	Hermann's tortoise	Yes	High	Used
Hagood and Bartles 2008	USA	Tu	Eastern box turtle	Yes	Low	Undet
Hammer et al. 2014	Australia	F	Multi	Yes	Low	Undet
Hibbitts et al. 2016	USA	L	Sagebrush lizard	No	No use	Low/no use
Honeycutt et al. 2016	USA	SA	Idaho giant salamander	Yes	Low	Undet
Jackson and Tyning 1989	USA	SA	Spotted salamander	Yes	High	Used
Koehler and Gilmore 2014	Australia	F	Growling Grass frog	Yes	Low	Undet
Krikowski 1989	Germany	F	Common frog	Yes	High	Used
Lang 2000	USA	Tu	Blanding's turtle	Yes	High	Used
Langen 2011	USA	Tu	Multi	Yes	High	Used
Langton 1989	UK	T	Common toad	Yes	High	Used
Lesbarreres et al. 2004	France	F, T	Agile frog Water frog Common toad	Yes	High	Used
Malt 2012	Canada	F	Red-legged frog	Yes	Low	Low/no use
Matos et al. 2017	UK	SA	Great crested newt Smoot newt	Yes	Low	Undet
McGregor et al. 2015	Australia	F, L, SA, T, TS	Multi	Yes	High	Used
Merrow 2007	USA	F, SA	Multi	No	No use	Low/ no use
Niemi et a. 2014	Finland	F, SA	Multi	Yes	High	Used
Pagnucco et al. 2012	Canada	SA	Long-toed salamander	Yes	High	Undet
Painter and Ingraldi 2007	USA	L	Flat-tailed horned lizard	Yes	Low	Undet
Patrick et al. 2010	USA	SA, T	Spotted salamander American toad	Yes	Low	Used
Rodriguez et al. 1996	Spain	L, TS	Multi	Yes	High	Used
Rosell et al. 1997	Spain	NR	Multi	Yes	NR	Undet
Ruby et al. 1994	USA	To	Desert tortoise	Yes	High	Used
Sievert and Yorks 2015	USA	Tu	Blanding's turtle Spotted turtle Painted turtle	Yes	Low	Undet
Smith et al. 2009	Canada	SA, T	Multi	Yes	High	Used
Van der Grift et al. 2010	Netherlands	F, SA, T	Multi	Yes	High	Undet
Veage and Jones 2007	Australia	L, TS	Multi	Yes	Low	Undet
Woltz et al. 2008	USA	F, Tu	Multi	Yes	High	Used

[1]Taxa: AS=Aquatic snake, F=Frog, L=Lizard, SA=Salamander, T=Toad, TS=Terrestrial snake, To=Tortoise, Tu=Turtle;
[2]Species: Multi = >3 species;
[3]Use levels: No use, Low, High;
[4] System evaluation: Used by a proportion of population, Low/no use according to extensive or limited study, Undet.= Undetermined or preliminary results.

In-situ research has been difficult to conduct, partly because of the uniqueness of and uncertainties within each location making multiple replicates difficult or impossible to enable statistical strength. Lack of replicates and multiple variables within and between years add to the challenge and to some extent point towards the value of more controlled experiments.

Controlled experiments suffer from removing animals from wild conditions and from the difficulty of mimicking the road environment. Until recent improvements in camera technology study has been hampered by the more invasive trapping and handling techniques being both time-consuming and interfering with natural responses of study animals.

Ex-Situ research may better able control confounding variables and conducting 'choice' experiments but lacks some of the real-time variables of the road situation such as noise, vibration and air-pressure change. The use of wild animals in captivity including finding suitable sample sizeor full representation of all population cohorts are of the additional concern. There is a further issue in terms of natural responses of different species within each species group that may vary widely, making a single model species for each species group impossible to identify.

Further details of the 11 'choice'-type studies are summarised in Table 5.2. These are mainly experiments where freshly caught adult wild animals were introduced to ex-situ passage system, and where a preference for structure type was recorded or simply whether or not to enter and move through or along a passage. It shows how few in number and general in inference the conclusions from the available research for each species groups are, with typically only one or two studies of key variables for each species group. Frogs, toads and turtles are most studied with 4 or 5 studies and lizards and tortoises the least with 1 or 2 studies. Almost all experiments were the smaller Type 5 passages although one is a Type 1 Wildlife Overpass study.

Table 5.3 provides further detail and comment on the 11 published and unpublished experimental passage and barrier choice studies in North America and the rest of the World 1989-present.

Table 5.2. Main conclusions on four main areas of variables study observations 1989-present, by species group category for this study

Species Group	Dimensions/ design	Light	Substrate	Moisture	Temp.	Barrier	General conclusions
Frogs	Dexel 1989						Guide fences to passages should be angled. Passages should allow movement in both directions and aligned along the natural axis of movement to a breeding pond. Use deflection boards at passage entrances.
	Lesbarres et al. 2004		Lesbarres et al. 2004				Some frogs may avoid entering passages while others may select to use them. Passage-floor substrate may increase passage use rate.
			van der Grift et al. 2010	van der Grift et al. 2010			Increased water/wetness to passage surface significantly increased their use by frogs, toads and newts.
	Hamer, et al. 2014						Tropical frog species may not react to passages in the same way as temperate species. Further field study is needed.
Toads					Langton 1989		Temperature may play a role in passage rejection when passage temperature is below critical minimum activity temperature.
			van der Grift et al. 2010	van der Grift et al. 2010			Increased water/wetness to passage surface significantly increased their use by frogs, toads and newts.
			Patrick et al. 2010	Patrick et al. 2010			Some toads may not exhibit tunnel floor substrate choice.
	Lesbarres et al. 2004						Some toads may choose to enter passages.
Salamanders/ newts			van der Grift et al. 2010	Patrick et al. 2010			Increased water/wetness to passage surface significantly increased their use by frogs, toads and newts.
			Patrick et al.2010				Salamanders may not exhibit tunnel floor substrate choice.
Snakes	Eads 2013		Eads, B. 2013	Eads, B. 2013			Smaller snakes passed through passages with water faster & more often than with soil substrate. Best culvert design is one with widths of at least 1.33 m, with either water or soil as the substrate.
			Kingsbury et al. in Andrews et al. 2015				Some snakes use smaller passages less frequently than larger ones.
Lizards	Painter, M.L, & M,F, Ingraldi. 2007.	Painter, M.L, & M,F, Ingraldi. 2007.					Natural light along passage upper surface may encourage increased level of passage acceptance and crossings.
Tortoises						Ruby et al 1994	Suitable barriers for desert tortoise are mesh with small holes smaller than tortoises head size. Tortoises walked away from solid fences. They willingly entered highway culverts.
Turtles	Woltz et al. 2008						Use of different sized passages was highly variable

							within and between species.
	Yorks et al. 2011	Yorks et al. 2011					In passage experiments, as natural light at the top of the passage increased, crossings increased. Artificial light had similar effect. for one species..
General/multi-species	Woltz et al. 2008						Use of passages was highly variable and variable between species. Not all animals should be expected to use passage on their first encounter.
		van der Grift et al. 2010		van der Grift et al. 2010			Increased water/wetness to passage surface significantly increased their use by frogs, toads and newts.

Table 5.3. Further details of eleven published and unpublished experimental passage and barrier choice studies: in-situ (EXP IN-SITU) and ex-situ (EXP EX-SITU) in North America and the rest of the World 1989-present. Location: AUS: Australia/Oceania, EUR: Europe, NAM: North America.

Authors	Location	Study type	Species	Study details in passage number, type and fence types
Dexel 1989	EUR Germany	EXP IN-SITU	Common toad *Bufo bufo*	Range of up to 12 different sizes of concrete pipes resting on woodland floor. Recommended guide fences as short as possible, two way tunnels, aligning tunnel axis with breeding pond and the use of deflection boards at passage entrances.
Ruby et al 1994	NAM Nevada	EXP EX-SITU	Desert tortoise *Gopherus agassizii*	Suitable barriers for desert tortoise are mesh with small holes smaller than tortoises head size. Tortoises walked away from solid fences. They willingly entered highway culverts.
Lesbarres et al. 2004	EUR France	EXP EX-SITU	Water frog *Rana esculenta* Common toad *Bufo bufo* Agile frog *Rana dalmatina*	Preferences of three anuran species for two kinds of 2.0 metre long concrete drain pipes One was lined with soil, the other bare. Amphibians could use or bypass tunnels. Water frogs *Rana esculenta* and common toad *Bufo bufo* showed a preference for the tunnels, whereas agile frogs *Rana dalmatina* avoided them. Among the individuals that chose either of the tunnels, all species showed preference for the passage floor surfaced with soil.
Painter, M.L, & M,F, Ingraldi. 2007.	NAM Arizona	EXP EX-SITU	flat-tailed horned lizard (*Phrynosoma mcalli*).	Use of simulated highway underpass crossing structures by flat-tailed horned lizards (Phrynosoma mcalli). Out of 54 flat-tailed horned lizards placed in the testing facility, 12 completed crossings. The 36-inch diameter culvert without skylights was used five times. The 24-inch diameter culvert with skylights was not used, and other culvert designs were each used once or twice.
Woltz et al. 2008	NAM New York	EXP EX-SITU	Green frog *Rana clamitans* Leopard frog *Rana pipiens* Snapping turtle *Chelydra serpentina* Painted turtle *Chrysemys picta*	Examined passage length, passage diameter, passage substrate type and passage light levels and also looked at barrier height. Showed use of passages was highly variable and variable between species. Not all animals should be expected to use passage on their first encounter.
van der Grift et al. 2010	EUR Netherlands	EX IN-SITU	Common toad *Bufo bufo* Common frog *Rana temporaria* Green frog complex *Rana spp.* Smooth newt *Triturus vulgaris* Great crested newt *Triturus cristatus*	An overpass 50 metres wide and 65 metres long above the A2 Motorway was opened in 2005. Amphibians were monitored after construction and it was found that addition of water features, via the experimental pumping of water into small pools that cascaded down to larger pools at the foot of the passage entrance slopes on either side of the open bridge, significantly increased their use by frogs, toads and newts.
Patrick et al.2010	NAM New York State	EXP IN-SITU	Spotted Salamander Ambystoma maculatum American toad Anaxyrus americanus	Studied natural population movements and four existing road culverts on woodland slope. Experiments with artificial barrier & short culvert sections (0.3, 0.6 and 0.8 metres diameter) & with different tunnel floor substrates did not show culvert choice.
Yorks et al. 2011	NAM North Carolina	EXP EX-SITU	Painted turtle *Chrysemys picta* Blanding's turtle *Emydoidea blandingii* Spotted turtle *Clemmys guttata*	Examined movements in response to varying light levels, and barrier opacity (ability to see through), passage size, passage entrance design. All 3 spp. responded poorly to a completely enclosed passage but as natural light at the top of the passage increased, crossings increased. Artificial light was shown to be as effective as natural light for painted turtle.
Eads, B. 2013	NAM Southern Indiana,	EXP EX-SITU	Eastern Gartersnake *Thamnophis sirtalis sirtalis* Eastern Ribbonsnake *Thamnophis sauritus sauritus*	The culverts tested 5 m length. Snakes passed through culverts. Minimal culvert size would seem to be >0.33m in width. For smaller culverts ribbon snakes passed through the culvert with water faster & more often than smaller culvert with soil substrate. Best culvert design is one with widths of at least 1.33 m, with either water or soil as the substrate to promote crossings.

Hamer, et al. 2014	Australia New Sth Wales	EXP EX-SITU	Striped marsh frog *Limnodynastes peronii* Green and golden bell frogs *Litoria aurea* Broad-palmed frogs *Litoria latopalmata*	Tested the behavioural response of three Australian frog species to a 12-m polymer concrete Type-5 surface road passage in controlled ex situ conditions with monitoring of light and temperature levels. Inconclusive findings but generally low inclination to move through passages.
Kingsbury et al. in Andrews et al. 2015	NAM Indiana	EXP IN-SITU	Copper bellied watersnake *Nerodia erythrogaster* Midland watersnake *Nerodia sipedon* Eastern Ribbonsnake *Thamnophis sauritus sauritus*	Ribbon snakes used smaller passages less frequently during tests using 8-10 metre long tunnels with or without substrates.

5.2 State of research and knowledge

Aspects of 52 studies concerning around 125 individual taxa (75 reptile and 50 amphibian species or sub-species) were also examined in terms of data on three study areas categories within them; *passage construction and use*, *passage environmental variables* and *barrier construction and use*. From the key publications there were 170 individual 'knowledge areas' identified, concerning these categories (Table 5.4.).

There was a little over twice the number of publications for amphibians as reptiles, however the amount of information on barriers was almost the same and overall the level of information was not that different; 45% were reptile and 55% amphibian. Around half of the passage studies addressed the quality of passage environmental conditions. Most studies addressed single locations. Most studies were for temperate bio-zones while less than 10% were from tropical or sub-tropical zones.

Snakes, lizards and frogs were the most studied of the seven discrete species groups, each representing about 20-25% of taxa, with 13 salamander & newt taxa, five turtle and two of tortoise studies. North America is the only location where detailed investigations of turtle passages have been made and desert tortoise is one of only two tortoise passage studies worldwide.

Details of the analysis of the studies are summarised in Table 5.2. and full details are recorded in Appendix C.

Table 5.4. Knowledge areas (n=170) identified from the 52 publications presented for each of the seven species groups. These are the number of reports/papers with any finding/s (high, medium or low assessed strength rating) for the three key areas of investigation; *passage construction and use, passage environmental variables* and *barrier construction and use.*

	Total papers	**Passage construction and use**	**Passage environment**	**Barrier construction and use.**	**Total knowledge areas**
Snakes	12	12	4	10	26
Tortoises	4	4	1	3	8
Lizards	9	9	4	4	17
Turtles	13	8	6	12	26
Total reptiles	**38**	**33**	**15**	**29**	**77**
Frogs	17	16	8	11	35
Toads	13	10	6	9	25
Salamanders & newts	15	15	7	11	33
Total amphibians	**45**	**41**	**21**	**31**	**93**
All Groups	**83**	**74**	**36**	**60**	**170**

Passage Design and Dimensions

Among the 52 studies nearly a quarter (23%) evaluated one passage, while over half (62%) evaluated 2-6 passages. The remaining 15% evaluated use and effectiveness of 7 to 20+ passages. Passages were primarily located on 2-lane highways (30%), 4-lane highways (17%), and smaller roads and dirt tracks made up around 25%. The highway configuration was not reported or could not be clearly determined by internet searching in the other studies reviewed. Some studies included more than one type of road. Dimensions and design of passages can dictate the permeability of wildlife movement (Iuell et al. 2003, Clevenger and Huijser 2011). Of the studies that reported the size dimensions, the majority of passages evaluated were Type 4 (< 10 ft/3.0 m) in diameter/width, and Type 5 small underpasses (< 3.3 ft/1.0 m). There were only two studies of Type 1 overpasses; one each in the Netherlands and Australia. Both appeared to function well in terms of records of individuals located within the passage with one species even recorded breeding on the passage. There were relatively few studies of Type 2 and 3 passages, with one study indicating that pathways beside a river/stream road bridge bringing value for general population connectivity and lowering levels of road mortality when no barrier exists.

Large culverts and bridges designed to accommodate water courses and water management may enable herpetofauna to safely cross under roadways. Some studies have shown that small engineered passages may be effective for significant levels of movement of target species but also many other members of the animal community (Pagnaccuo et al. 2012). Of the studies we reviewed, 58% focused on engineered passages for herpetofauna, while 34% consisted of non-engineered (not designed for animal movement) structures. A few studies (n=3) contained a mix of engineered and non-engineered passages. For California almost all of the engineered amphibians passages built are small Type 5 passage and barrier systems and for reptiles (tortoises) most are Type 4 box or cylindrical culverts. For amphibians the size of passages varies in California from 200-500 mm/ 8-20 inches in diameter. Typical drainage-wash culverts in desert habitat are 1.0 m /3.3 ft culverts sometimes placed in series (Figure 5.1.). These can be very long but may be used by fauna including tortoises (Boarman et al 1998).

There is repeated anecdotal mention in the literature that passage-use by amphibians generally (including passage entry hesitation/rejection and turn-backs) may relate to tunnel length (Iuell 2003, Clevenger and Huijser 2011). These recommend that the longer a passage is, the larger the cross sectional area/volume should be, to maximise probability of passage use and a full crossing.

Several studies comment on passage use with respect to passage diameter and length, in some case with manipulation of passage light level, e.g. for turtles (Yorks et al 2011). Increasing passage size and shortening passage length appears to increase passage use levels, but the thresholds for enabling all or a set percentage of animals to use a passage for a full crossing without turn-arounds/turn backs has not been determined and may vary between species, although there is some evidence that newts may explore a passage several times before making a full crossing so there may be a learning aspect to passage use (White et al. 2017). Passages with open gratings above have been proposed and used on low-speed roads, but may not be practicable due to safety concerns on high-speed roads. Small polymer concrete 'surface tunnels' with slotted roofs are the only open-topped passages used on high speed (60 mph upwards) roads and these have been the subject of a more detailed studies (post 2010) with the benefit of infra-red night cameras that have become more easily available over the last 10 years.

Most herpetofauna, especially those in closed canopy habitat experience low light conditions and many live underground. Response to passages and use made of them may relate to a range of factors according to the behavioural cues animals are sensitive to at the time of passage encounter. It is hard to determine the key factors; sense of confinement, confusion, movement away from sunshine or star or moon light, anticipation of predators or other possible factors.

Generally the evidence does point towards the expected view that passages should be as short in length and as large as possible in diameter and this generality is important because usually the cost of a crossing structure increases with size in terms of fabrication, construction and maintenance. Published guidelines stating sizes are rarely referred to in the published literature and are very often an adaption of a standard drainage or road/livestock/watercourse passage structure used on a road scheme. There are studies showing use of small culverts if the system is well designed. It is generally not known for each species what level of passage use may be achieved using optimal or compromised designs and few studies cover all life stages. Use levels are likely to vary considerably may vary between sites.

Due to lack of detailed study, it is not known at what size passages generally start to limit the proportion of a population moving safely across a road, but overpasses are the only passage that were reported as being suitable enough to sustain a range of micro-habitats where amphibians and reptiles may shelter. Anecdotal information suggests some will hide in soil and leaf-filled Type 5 passages (Figure 5.2.).

Figure 5.1. These 3.0 ft /900 mm concrete culverts are placed to accommodate flood events at large desert washes. They may be used by reptiles including desert tortoise but may not have engineered barriers. Large boulder rubble (rip-rap) may be placed to act as turtle barrier between the end of the culvert headwall and the beginning of the barrier fencing.

Figure 5.2. This small 'stilt-tunnel' (cast concrete sides and roof with natural soil base) on a 2-lane road near Berlin, Germany, has an extensive late-season leaf litter component under which *Triturus* newts may be found sheltering inside the passage and around it's entrances. Note the deflection panel made from the galvanised sheet metal fence material with overhang.

Inter-passage distance/Passage-barrier interface
The measured proportion of a herp population using a passage system or even a subset of a population moving towards a passage system actually making a successful passage is normally well under 50%, usually under 30% and often probably just a few percent. Good data for reptiles appears very scarce.

The orientation of the passage/s to the general direction of movement of movement or migration is mentioned by at least two authors as important in achieving higher passage use levels. This orientation is often the direct line from the emergence/overwintering area to the breeding/feeding area and for amphibians may be more important when the breeding waters are small ponds and pools as opposed to a broader expanse of wetland or stream.

For amphibians the relationship between inter-passage distances and the angle of barrier approach to create a funnelling effect is considered critical for species to locate passage entrances. A zig-zag design with barriers angled from the road edge by up to 45 degrees and the likelihood is that the animal is more likely to approach the passage entrance other than from the side (at 90 degrees) and has less chance of walking past the entrance. Angled barriers leave unoccupied habitat 'trapped' on the road-side of the barrier. These can be further from the road edge and less attractive in terms of maintenance and interference of the structure with other land uses. For practical reasons a compromise is made and barriers built flush with road boundary fences. Where passages are not in close proximity with angled barriers there may be reports of animals 'giving up' directional exploration along barriers and turning back. Some female animals may reabsorb unfertilised eggs and not breed in that year.

Deflecting boards placed at 90 degrees to the passage entrance are generally considered to be important in preventing 'walk-past', however one enclosure trial for turtles found that a lack of deflectors did not influence passage use rate.

Entrance rates into passages have been studied in several experimental settings. For instance, ex situ choice experiments were conducted with two species of Anuran; green frog, leopard frog and two species of freshwater turtle; snapping turtle and painted turtle (Woltz et al. 2008). Approach to the tunnel entrance was not directional but the animals were placed in a central chamber with four options each at 90-degree angles. Trials considered passage length, passage diameter, passage substrate type and passage light levels.

In the choice experiments snapping turtles refused to move into a passage for 15 minutes most frequently (56%), followed by green frog (32%), leopard frog (23%), and painted turtles (16%). However they were done with small sample sizes, generally under 20 animals per test and often under 10 individuals.

In another study the behavioural response of three tropical Australian frog species, (two ground dwelling tree frogs and one aquatic frog) were tested in a 12.0 m long polymer concrete Type 5 surface passage (Hamer et al. 2014). The mean time taken for an individual to enter the passage was 14 min:22 seconds. There was some evidence of directionality in the movement of two species but use did not appear to relate to air temperature, humidity or light levels inside the passage. The proportion of frogs entering the passage (tunnel usage), and entering and exiting the tunnel at the opposite end (tunnel efficiency), among the three species was low; 0.13 and 0.05, respectively and recommendations called for further in-situ research.

Passage environment related variables

Undoubtedly the most valuable information from monitoring and research on passage performance comes from rigorous analysis of attributes or variables associated with some degree of movement and beyond one or two 'test' animals. Use of passages by some amphibian and reptile species has been said (not surprisingly but with limited evidence) to be dependent upon it mimicking sufficiently the key ambient conditions for movement (light, moisture, temperature, substrate) in the species natural habitat (Langton 1989, Schmidt and Zumbach 2008, Jackson 2015). Also important are passage dimensions, which influence several of the environmental variables. Physical features (type, design or dimensions) of passages were the most studied attribute among the sources we reviewed, followed by single tested attributes; ambient light level, substrate and fencing (all n=7) and moisture/humidity (n=6). Temperature was the least studied variable among sources reviewed.

Surprisingly a majority of the studies did not report (i.e. not research) any environmental variables tested in their research and monitoring. This is likely due to many studies not having a fully quantitative design to test the physical and environmental factors in controlled settings, but merely being interested in whether the target species approaches and uses a passage or passage system and if possible some anecdotal evaluation of the acceptance or rejection level/rate of the passage system.

Light levels

Light levels inside a passage may play an important role in passage acceptance by many species. This is largely influenced by passage dimensions. This is probably for behavioural reasons with passages mimicking animal burrows or caves and movement towards 'hiding' habitat, not stimulating the animals immediate need at the time of passage entrance encounter. The evidence for amphibians and turtles is stronger than for other reptiles. At night, background star and moonlight light levels may be important for navigation and directional cues in some species. Reflection of moonlight on breeding water surfaces at night has been suggested anecdotally to play a role in visual navigation during migrations from dry land to aquatic habitats. Although we are not aware of a published study, Jackson (1996) noted that absence of light was associated with tunnel hesitation in spotted salamanders and noted that once artificial light is provided the time it takes salamanders to enter and pass through the tunnels is dramatically reduced.

The inferences from the multi-study anecdotes for amphibians (Krikowski 1989) combined with the rigorous testing of turtles by Yorks et al. (2011) gives reason to believe that light levels are a significant factor in passage use levels. Light levels relate to passage dimension with larger passages providing greater light levels from each end, whereas low light levels may be a factor in passage entry hesitation and turn backs. However, there have been no controlled experimentation on effects of light levels on passage use by snakes, tortoises or amphibians. However, selective use of larger or open top passages is indicating that light levels are a significant factor in passage use in general.

The light levels discussion leads to consideration of how big a passage needs to be for its length, which have been guess-estimated (FMT 2000, Iuell et al. 2003) but also the comparative benefits of surface passages over buried passages and the potential use of artificial lighting at the ends of or within passages to help attract movement. Artificial lighting has been used in a passage structure on Route 7 in Connecticut (Jackson et al. 2015). There is anecdotal mention in Europe of use of Type 5 passage with small LED roof lights in an experimental design.

A number of recent studies (post 2013) using 500mm slotted surface passages that allow natural lighting conditions have been instigated but data is not yet published (Figure 5.3.). In California over two-thirds of the recently (post 1995) installed herpetofauna passages (Langton et al. 2015) are slotted polymer concrete surface tunnels of 200-500 mm diameter. In another ex-situ study, behaviour by turtles towards simulated passages was carried out, varying passage-top light levels (Yorks et al. 2011). Species studied were painted turtle (n= 833), Blanding's turtle (n= 49) and spotted turtle (n= 49). Also examined was passage size, tunnel entrance design, and effects of artificial lighting for painted turtles only. Results found that all three species responded poorly to a completely enclosed passage (0 % available light treatment). As the amount of natural light transmitted through the top of the passage increased, successful completion of a passage crossing increased.

Figure 5.3. Engineered gratings within the roof of a reptile passage, placed to increase internal light levels along a buried passage, designed to connect an area of heathland and woodland in The Netherlands.

Substrate

There may be conflicts between trying to make the inside of a passage more like natural habitat and trying to keep it clear, bare and unblocked with natural debris and rubbish (Figure 5.4.). Bare concrete or other passage floor surfaces may be dry and construction residues may be toxic to amphibians (Brehm 1989). Natural substrates were first used both to level the bottom of a cylindrical culvert and to prevent caustic alkaline residues/salts coming out of freshly made concrete culvert and harming the skin of animals, particularly thin skinned amphibians. Polymer concrete passages were adapted to overcome this problem by virtue of their inert properties not requiring a substrate (Brehm 1989). Despite some low-inference studies on anurans (Lesbarres et al 2004), salamanders (Patrick et al. 2010) and on snakes (Eads 2013), there is almost no scientific information published on the importance of substrate quality in relation to passage use.

Passage floor substrate has been studied in several experimental settings. For instance, preferences were tested for three anuran species for short sections of two kinds of concrete amphibian passage (Lesbarres et al. 2004). One was lined with soil, the other a bare concrete pipe. In the choice, the amphibians could either move though the passage sections or bypass them. Water frogs and common toads showed a preference for the tunnels, whereas agile frogs avoided them, but life-history differences between species alone did not explain these results. Among individuals that chose either of the passages, all species showed a significant preference for the passage lined with soil. It was concluded that species may differ in their preferences and in their likelihood of using passage underpasses according to its qualities. However the experiment was conducted with tunnels only 2.0 m long, which would have removed to a large extent background light and temperature considerations as variables.

Figure 5.4. Type 4 cast concrete 'stilt-tunnel's with side walls built on foundations and soil in contact with the natural water-table were developed after 2000 to encourage an environment more like that outside the passage. Heikamp, Netherlands.

Moisture

There are at least anecdotal indications that passage moisture/humidity levels play a role in passage acceptance by some salamanders (Jackson and Tyning1989) and this might be anticipated due to the life history of amphibians and aquatic and semi-aquatic reptiles. Many amphibians and particularly salamanders are highly active during heavy rain and passage wetness may generally improve passage use levels much as it improves above ground activity by most amphibians. Some salamanders will stop overland movement when rain stops or even if they simply encounter dry ground under a tree canopy.

Although California tiger salamanders were shown to use both wet and dry passages, passage speed was observed to be slightly increased within wetted passages (Bain 2014). Reptiles appear less sensitive to dryness but rainfall may also trigger increased activity. Some snakes and turtles moved through wet or flooded passages more often or faster than dry or damp tunnels (e.g. Eads 2013). Overall, the evidence for benefits of moisture is stronger for amphibians than for reptiles (Hibbitts and Walkup 2016).

Temperature

Passage temperature may play a role in passage entry hesitation and use (Langton 1989) and probably also turn-back rates if the centre of a passage is colder that its sides. In temperate conditions species may emerge as air temperatures move rise above critical thresholds and when this happens a structure buried in cold ground may be too cold for them to use for a period of days or weeks. Temperature may fluctuate above and below minimum levels for movement, influencing passage use. Heat (a passage being too hot) may also be a possibility.

Relevant factors are passage floor substrate temperature and air temperature, mediated by passage air/floor temperature or both. Temperature levels may be influenced by wind speed and wind-tunnel effects within the open ended voids that passages form. Alignment of passages may influence passage temperature with respect to their orientation to prevailing wind direction.

There are anecdotal reports of flat heat mats of a kind used in vivaria being used in some experimental passages in Europe to use warmth to attract and encourage passage use by reptiles.

Structure within Passages

There are very few studies of shelters/furniture inside smaller (Type 4/5) passages and the extent to which they might encourage passage use. However in some Type 4 and larger passages logs, rocks, old tree stumps and artificial refuges have been placed (Figures 5.5 and 5.6). to enable sheltering and reduce exposure to predation(Andrews et al 2015).

Figure 5.5. Root wads and tree branches are often placed along berm walls on overpasses and used to provide shelter for herpetofauna and other wildlife along wildlife overpass and underpasses.

Figure 5.6. Small tree roots and branches placed along a berm wall on a wildlife overpass in The Netherlands.

Barriers

Barriers (stand-alone fencing and built-in guide walls) for the most part are crucial for passage use as they guide animals to crossing structure entrances designed to move them over or under roads (Figure 5.7.). Over two-thirds (65%) of the studies (both in-situ and ex-situ) had barriers as part of the system, while around one in five systems (21%) evaluated passages that were not associated with barriers. All of the systems in California comprised both passages and barriers. In some cases barrier length was relatively short.

There are indications that barrier alignment (angle to the passage entrance) and presence of deflector boards (swallowtails) play a significant role in animals not 'walking past' a passage entrance (Brehm 1989). Distance between passage entrances and angle of barrier approach may play a role in passage entrance use/rejection rates, whether this is a function of the proportion of migrants 'arriving' at an entrance, or the proportion in contact with a barrier or exploring away from the passage entrance. Barriers need to be high enough not to be climbed and an overhang is important for some species. Height and opacity (ability to see thought barrier) may be very important in terms of species reaction to the barrier and likelihood to walk along it as opposed to try to climb or move away from it.

Height and shape

Generally the requirement of species groups is broadly similar and body size (generally body length) and ability to climb and jump is a major factor in barrier effectiveness. This varies greatly between species with usually frogs and snakes being good climbers/jumpers and toads, turtles and tortoises being less adept. Barrier durability has a strong effect on passage effectiveness as has the presence of an overhang. Barriers generally range from 300-600 mm in height. Most species are contained by a barrier 1.2 m high with an overhang of 120 mm, dug into the ground 200 mm. All groups have species that may be adept at digging or burrowing under barriers or that live in communities with burrowing mammals, so the barrier must be designed not just for the target animal but those capable of undermining and damaging it.

Length of barrier/turnarounds.

Several barrier types are curved backwards towards the direction of approach so that they only block movement in one direction and are harder to climb or to jump over. They also help reduce the amount of material needed and are less obtrusive in the landscape but may be more easily overgrown by grasses. In a study comparing the effectiveness of barrier heights at 300, 600 and 900 mm in blocking the movement of turtles, Woltz et al. 2008 found that 300 mm fences were too low to prevent most animals climbing over them, rendering them ineffective.

Barrier length

Barrier length is dictated by a range of factors including project scope, land ownership boundaries and cost of installation. Barrier position and length in real-road situations is rarely fully discussed and appears sometimes to be often a compromise based upon multiple factors. Most barriers focus in high density movement areas and do not cover the full extent of low density movements of a population or meta-population.

Barrier materials (type)

There has been a very wide range of experimentation with different types of barrier and it is clear that this is a major component of cost in constructing the passage system. Special arrangements are needed where barriers cross-vehicular side roads. Barrier types range from re-cycled crash barriers and line poles to purpose made barriers constructed from galvanized wire, mesh hardware cloth, plastic, metal, concrete and polymer concrete.

Many amphibian barriers are made from temporary thin plastic sheeting that may last under one year due to tearing or UV damage causing brittleness. Metal mesh/sheet and thick plastic sheet/moldings are typically designed to last 10-25 years or more. For installations that are designed to be permanent (50-100 years) concrete and polymer concrete are most reliable. Metal sheet may last according to its chemical composition & coatings and the degree of saturation of soils.

Orientation to Passage entrances and barrier translucency

The orientation of barriers to passage entrances may play an important role in passage use by herpetofauna. One of the early discoveries was that amphibians walked past passage entrances, either not recognising them as a way to disperse or avoiding them. Several studies have addressed this. In the earliest experiment, a choice of Type 5 passage size was offered to migrating common toad *Bufo bufo* by placing circular concrete drainage pipes of differing diameter on a deciduous woodland floor and measuring the response of migrating individuals (Dexel 1989).

Figure 5.7. Fine wire (invisible) tortoise barrier fencing along an Interstate Highway in California desert habitat at a culvert underpass.

The passages were placed in-series across the densest concentration of a large directional toad migration. The main recommendation was to arrange barriers, so that they are as short in length as possible (between passages) by angling them towards the passage entrances and for the use of passages that allow movements in both directions. The other conclusions for amphibians were the benefits of aligning the axis of a passage with the most common direction of migration to the main breeding pond, and the use deflection boards next to passage entrance to maximise the number of animals diverted into the tunnel entrances.

Studies show that several species of Chelonians (turtles and tortoises) will tend to walk along barriers that they can see through and move away from those that they cannot see through. Tortoises following fencing may die from heat exhaustion if they do not find shade cover. This response may assist in design of barriers according to the desired response. Several species of frogs, snakes and turtles were able to climb and spent significantly greater amounts of time interacting with hardware cloth mesh fencing than plastic solid barrier fencing (Milburn-Rodríguez et al. 2017)

These results suggest the importance of designing road passage structures for freshwater turtles that provide adequate passage lighting, in combination with specific entrance designs that minimise passage entrance 'walk-past'. Therefore, deflection boards in front of passages may increase passage use (Brehm 1989, Dexel 1989).

Barrier Ends and Access Road Treatments

The outer ends of barriers and gaps at access roads can result in displacement of road mortality hotspots away from the original core area/s. Commonly barriers are not long enough and must be extended to cover a wider area of habitat. The use of turn-arounds at the barrier ends is well-established practice for all groups (Figure 5.8.) but effectiveness however is assumed rather than proven. Often they are not well designed and 'overshoot' occurs creating displaced mortality hotspots (Gunson 2010, 2015).

Other strategies include ending the barriers at natural landscape features precluding onward movement (e.g. cliff bases) and adding large rocks or rip-rap at the ends to simulate a natural barrier and to redirect animals. This may be more effective for tortoises and turtles but may be an attractant to other reptile and amphibian species for cover and food resources.

Private and public access roads along a fenced road are a particular challenge that is often inadequately addressed on many projects. Cattle guards or similar designs, including purpose manufactured 'stop grids' that are effective for the smaller species only (Figure 5.9.) make it difficult for small animals to cross but allow small animals to escape back into the habitat if they fall through the grating has been used with some success. Other options that have been used include gates with a base treatment such as addition of a rubber flap, to exclude small animals and most often, turn arounds at each side of the access road. This is an area where further investigations and designs may hold value.

Figure 5.8. Tortoise fence 'turn around' at dirt road junction within small Caltrans easement (I-395).

Barrier repair/maintenance

Figure 5.9. A small 'stop-grid may help prevent small amphibians (small frogs toads and salamanders) from entering a main road via a side road according to the width of the grating.

Projects for all species groups mention the failure of barriers due to a lack of general repair and maintenance of damage/holes in the barrier during the period of study. Other studies highlight limited or poor design, poor installation, poor materials, damage by large animals, weather damage and erosion, wear and tear and other factors. Poor design has played a role for all species groups and appears hard to correct. Post- installation maintenance is vital for the value of the passage installation investment not to be wasted.

Summary

We assessed the quality and quantity of information available that addressed overall passage and barrier qualities and use level, per species group (Table 5.5.). We categorized the quality of information available for Passage Construction Use, Passage Environment and Barrier into categories of High, Medium, Low, Very Low/None. A high rating may be a good confidence in a small detail and a low rating may be brief evidence of a significant finding of wide application, therefore the strength ratings do not necessarily reflect the relative importance of studies to each other or imply low intrinsic value of studies. Note: in the table NA means either Not Available or Not Applicable to the study. Species group information summary colour codes according to relative extent of study – see Table below.

Table 5.5. General assessment criteria for considering the selected sample of amphibian and reptile mitigation system studies in terms of information provision strength for overall passage and barrier qualities and use level, per species group.

Species Group	Passage Construction & use	Passage Environment	Barrier
REPTILES			
Snakes (Aquatic & terrestrial)	Snakes may use small Type 4 & 5 passages to some extent and overpasses. Generally closed culverts of over 1 metre span (Type 4) appear to be preferred to smaller sizes but smaller sizes will be used by some species. Few studies.	Passage use may be enhanced by having good quality habitat closely adjoining the passage entrance or as a part of it in the case of overpasses.	Snakes may be capable of negotiating solid vertical barriers if the barriers are shorter than the snakes length and do not have an overhang. Overhangs may be important to prevent climbing over.
Tortoises	Tortoises will enter Type 4 passages and repeat use has been recorded in a few individuals.	Passages along stream beds thought to be most effective. Tortoises may burrow in culverts with deep sediment. Tortoises can get caught in rip-rap used for barriers or in front of passage (unpublished report).	Small mesh prevents climbing. Tortoises will walk along barriers that can be seen through but tend not to follow solid walls. May follow mesh barriers for several kms & die of heat exhaustion in absesbce of shade structures.
Lizards	Lizards may use small Type 4 & 5 passages to some extent and overpasses. Generally closed culverts of over 1 metre span (Type 4) appear to be preferred to smaller sizes but smaller sizes will be used by some species. Very little information.	Passage use may be enhanced by having good quality habitat closely adjoining the passage entrance, within the passage, or as a part of it in the case of overpasses.	Lizards may be capable of negotiating solid vertical barriers according to their size and agility. Some can climb hardware cloth fencing. Overhangs may be important to prevent climbing over by non-specialist climbers.
Turtles	Turtles may use small Type 4 and 5 passages at least to some extent.	Light levels in passage and passage size/length and state of flood may influence passage use rates and speed of crossing by turtles. This will vary between species.	Turtles may be capable of negotiating solid vertical barriers according to their size and agility and may dig underneath them. They may walk along barriers that can be seen through, but tend not to follow solid walls.

Species Group	Passage Construction & use	Passage Environment	Barrier
AMPHIBIANS			
Frogs	Frogs may use all crossing types and passages at or above 500 mm diameter are preferred with a non-concrete floor but there may be high variation in behaviour of species.	Light levels in passage and passage size/length and state of flood may influence passage use rates and speed of crossing by frogs. This will vary between species.	Frogs require high barriers of 900mm or more and with an overhang for some species. May not locate passage entrance without deflection boards
Toads	Toads may use all crossing types and passages at or above 500 mm diameter or smaller if slotted surface.	Light levels in passage and passage size/length, temperature and wetness may influence passage use rates	Toads generally do not jump as high as frogs but may climb and require smooth sided barriers of at least 450 mm. Barriers should be angled not flat to the passage.
Salamanders and newts	Salamanders and newts may use all crossing types and passages at or above 500 mm diameter or smaller if slotted surface.	Passage wetness seems particularly important in terms of use and speed of passage. temperature and light levels may also influence use.	Some newts and salamanders are very adept climbers and an overhang is required. Others hardly try to climb at all.

HIGH	Well or reasonably defined and extensive study. Good sample sizes, practical results and suitable analysis. Contribution to needs of species and or wider application to species group generally.
MEDIUM	Useful information derived from a systematic approach. Acceptable results sometimes limited by sample size or other uncertainty. Appears to show significant trend/s at least
LOW	Study may have been constrained by unanticipated issues or events. Variables may not have been tied down enough for robust conclusion. Aspects of design not ideal. Small sample size limits strength of interpretation.
VERY LOW/NIL	Limiting study design or spoiling event during study. Observational and anecdotal from low sample size. May reflect unusual study conditions. No information or speculative.

5.3 Conclusions

Passage system types and frequency of construction

Generally we found a paucity of studies of the effectiveness of road crossing passages for herpetofauna. There are a few studies of larger (wider) passages but not many of these exist in Europe and the USA. The review shows that the small passages are the main type presently used for amphibians and reptiles although this may reflect study emphasis and availability. Most but not all purpose-built/engineered systems are under 3.0 metre diameter/span in any direction. This is perhaps not surprising because structures spanning a wide main road are expensive to build and to maintain. Wildlife passages have largely not been prioritized in the road construction decision making process although awareness of the need is growing. With exceptions of large wildlife overpasses, many of the passages studied were built with a function of drainage provision, pedestrian or small vehicle access and wildlife connectivity. In some cases the position of drainage culverts and under bridge stream edge was simply adjusted to encourage dual water and wildlife passage functions. Passages exclusively built for wildlife are typically Type 4 passages, often box culverts under 3.0 metre span and Type 5 micro-tunnels under 1.0 metre span. Increasingly slotted surface passages have ben preferred. A number of companies have started to design and market engineered passage and barrier systems.

Barrier and passage qualities

This review found limitations to the quantitative conclusions that may be drawn regarding performance and effectiveness of barrier and passage mitigation systems for amphibians and reptile species. The response of individuals and populations to artificial barriers and passage environments is challenging to measure and to draw firm conclusions from. These studies often require expert application of substantial resources over extended periods to assess passage use accurately. Specialist techniques to achieve this have developed relatively recently, to overcome the issues relating to interference in study-animal behavior from trapping and handling. There also appears to be considerable variability in needs and behaviors within and between species & their habitats (and between species groups) and a wide range of physical and biological variables that may impact study results, in often unpredictable field conditions.

The differences between types of built passage structures and of road width and traffic intensity adds further dimensions to complicate study design, analysis and comparison between sites. Nevertheless some general passage-use or non-use findings have emerged in over 50 years to provide basic guidance in terms of the approaches more likely to achieve practical mitigation objectives in different circumstances.

Barriers

Response to encountering a barrier may include most obviously trying to climb over them, digging down beside them or hiding in gaps at their base, walking along or moving away from them. Reaction might vary according to materials and whether or not the animal has ‘memory’ of occupying habitat beyond the barrier and if this is the case, the extent to which the individual has inbuilt propensity and physiological flexibility to search for and locate alternative habitat for survival.

Barriers are simpler structures than passages and are easier to judge in terms of their function which is often both to prevent movement onto a road and to guide movement towards a passage entrance. One issue raised frequently in the literature is the importance of barrier durability and its regular ongoing maintenance. If not carried out this is catastrophic to the good function of the designed system. Angle of approach along a barrier to a passage entrance and the use of deflector boards at or close to the passage entrance to encourage passage entry appear also to be important considerations in terms of level of passage use. The extent to which animals follow barriers and the probability of an individual being guided to a passage entrance together will influence potential passage use levels in addition to decisions whether to move into the passage and all the way through or to turn back..

There was little to no information on the effectiveness of barrier end treatments, such as turn-arounds, which are a common feature of barrier installations and often mentioned as failing. There was no information on the effectiveness of cattle guards or other solutions to driveways and access roads intersecting barrier systems.

Passage environment

Looking at passage characteristics in terms of 'naturalness', the Type 1 road tunnel or wildlife overpass passages, as natural or near-natural habitat should be close to those of pre-impact conditions and may also be enhanced by micro-managing habitat. The main limitation for overpasses in terms of continued free dispersal is the relative narrowness of open habitat that may constrain dispersal at both the localized and landscape scales although this is not always the case in fragmented landscapes.

This is also the case to a large extent with Type 2 and 3 passages; larger bridges (underpass passages), often spanning a river or valley. With high bridges and narrow roads the only influence of the road on the passage may be slight shadow or shaded conditions together with more general road-effect impacts such as noise and pollution. Sometimes however concrete structures and boulder placement limits access underneath them for some species. Generally most species might be expected to readily move through them however this seems worth checking as it may not be the case for all species and habitat under bridges is sub-optimal or degraded. Extent of passage use may diminish as they become smaller in size. Confirming the level of use or not of such passages by different species is essential background information because these are the highest proportion of wildlife passages yet very little is known about them.

Type 3 large wildlife underpasses are also expected to be effective for smaller species. However, there are very few studies that include robust monitoring for small reptiles and amphibians. Therefore, effectiveness of these structures are largely unknown but likely associated with species life history and space-use characteristics. Open habitat specialists may readily pass through these structures but other species may require internal structures and, as with some mammals, built-in ledges to be effective. Very long structures under wide highways may also have different light, moisture and temperature characteristics than the surrounding environment, making them less suitable for many herpetofauna species.

It is the smaller Type 4 & 5 passages where key variables that are considered most likely to influence passage-use have been most intensively studied. These are principally; passage light levels, floor substrate type and quality, wetness/humidity and temperature. These factors interact with each other.

Passage volume (length and cross-sectional area) which from anecdotal evidence, published overviews and studies published in other languages is considered to interact with biotic and abiotic variables. These variables likely influence the choices animals make such as 'hesitating' or 'balking' at the passage entrance, or having entered a passage ‘turning back’/’turning around’.

Many herpetofauna spend large amounts of time hidden and buried and so they are well adapted to moving in total darkness and in high levels of confinement. There is some evidence however for amphibians that perception of light at the end of or within a passage (normally from above, with slotted/grated top passages) may be a cue to passage use, whether this is a simple cue to anticipated outcome (movement in a given direction) or the recognition, cognitive or inbuilt of sun, star or moon light and rainfall in navigation.

The smaller and longer the passage is, the lower the day/night time background light level is inside the passage. The literature suggests that natural light levels (including at night) generally increase the probability of a favorable passage use outcome, however the ‘reward’ based motivation for passage use or non-rejection is poorly understood in herpetofauna and may vary greatly between groups.

Passage floor substrate type as a variable is likely to be important. From a practical perspective a flat floor mimicking that of the natural surroundings, albeit bare, is expected to be preferred to a flat or curved artificial surface. Since soil is generally not an efficient conductor of heat and cold, this substrate may help buffer the passage bottom from temperature fluctuations. However, it is also clear that the inert floor of an artificial passage, as long as it is free from harmful chemicals and similar in temperature, may allow an unhindered crossing with firm foothold and good visibility. Substrate quality may also be important in determining wetness or moisture levels. For many aquatic species water-filled or flooded passages may offer a preferred passage environment for swimmers and this is not widely mentioned in advisory publications. There may be questions regarding how to ’finish’ the detailed interior of a passage to best effect for species with different needs. This will vary from passages that are permanently flooded so that aquatic and semi-aquatic species can swim straight through them, to those that may remain dry, bare and featureless.

Temperature, light and moisture is also of importance to the behavior of reptiles and amphibians, which can be very sensitive to small environmental fluctuations. Slotted or grated surface passages allowing air and water conditions in passages to follow external weather and minimizes the difference between internal and external conditions may hold benefits, particularly on low speed roads although they may also expose users to a greater physical (noise, air pressure and vibration) and chemical impact from the road environment than a fully buried passage.

Over the past 40 years or more all of these variables have been the concern of passage designers. However, despite progress beyond identifying systems that ‘*don’t work’* to those that *‘work to some extent’*, it has been difficult for researchers to identify the precise needs of any individual species or community, and there is no indication of success criteria being developed to assess outcomes.

Passage-use

For an amphibian or reptile to habituate or ‘learn’ to use a passage, a presumption might be that its use is ‘imprinted’ during navigation and orientation over the first few months or year of its life as a neonate/juvenile, so that both sides of a passage system becomes a part of its ‘ learned’ range area. Juveniles and young adults may also explore and learn the location of favorable habitat and it may be that they can learn and adjust to use passages on a regular basis. There is some evidence that the proximity of a breeding area to the passage will increase the extent of its use, however sensitive areas close to roads may suffer greater exposure to road pollution effects.

This scenario is different to adults encountering suddenly severed habitat and finding an obstacle or change within their established range. Therefore the life-span of species as much as its ability to 'explore' may play a role in how quickly as well as how positively, different populations may adapt to changes to their general movements, after placement of barriers and passages.

The capacity to adapt may also relate to traits for vagrancy or the pioneer exploration, which varies between species and populations. These may include sub-dominant individuals ousted from a core population area and dispersing long distance. To this extent and especially for long lived species, it may be expected for some species (perhaps especially long-lived species) to take many years or even decades for populations to adjust to a passage system and for new carrying capacity to establish as the population adapts to its new space. Success and failure judgements for systems therefore must be very carefully set and may take many years to assess correctly.

The relationship of animals to the habitat on either side of a barrier and passage system is therefore central to the question as to whether or not there is a need for them to use a passage and how often, and whether the need is in terms of that individuals survival or, more generally the 'need' of the population not to become genetically isolated as a result of severance, or both.

In some circumstances, all or a high proportion of individuals may need to cross a road in order to reproduce or to feed in a particular habitat found on one side of it, while in other circumstances there may not need to be any passage use to enable annual breeding, but just to allow low levels of genetic exchange sufficient to prevent long term isolation and inbreeding. If habitat critical to one stage of the life cycle is positioned just on one side of a road and regular and large scale passage use is needed, the issue of how large and how spaced-apart passages are, and the proportion of a population that may use a passage occasionally or routinely becomes more important in system design. Therefore, it seems essential to define the objective of a passage in relation to population-level or genetic connectivity.

It is possible that in some circumstances animals using a passage may simply make one journey and then be 'lost' to the its population that mainly or exclusively occupies one side of a road. This may or may not 'matter' in terms of population survival because in some species (notably many amphibians) annual survival rates may be naturally low and the important factor is recruitment of the new cohort and its ability to use the passage for the first time. In other cases mass movements may be unnecessary or even undesirable. Therefore in discussing passage use, it is important to do so with a clear context of the spatial orientation of relevant micro-habitats in the pre-impact and the future severed landscape and their importance to each species in order to properly define and to try control a clear process.

To-date there is almost no information on passage use over the lifetimes of individuals, let alone generations or for whole populations, showing the extent of use of passages and the population reaction. The amount of information on individually marked animals following barriers, using a passage and returning through a passage itself is limited to a few studies. So the state of understanding is really that passage systems can operate for some individuals, but the proportion of an adult population doing so may be low (normally under, often well under 30%) and sometimes barely detectable, so overall there could be residual risks of population decline and genetic separation from inadequate mitigation even from extensive and costly mitigation actions that appear superficially to 'work'. The percentage of a population that requires population level connectivity may be high for migratory species and lower for non-migratory species. Therefore, permeability goals must be well thought out and defined for target species and communities. Spatial population viability models may useful tools in defining species specific permeability needs and goals but should be used with caution.

General

The evidence presented from the literature review indicates the following for passage types;

1. If the passage design purpose is to enable repeated movements by multiple individuals to enable large scale dispersal across a landscape, particularly one identified for strategic wildlife connectivity, then Type 1, 2 or 3 passages are needed. How far apart these need to be will vary according to the species present and the habitat/landscape.

2. If the aim is to enable large numbers of animals to move backwards and forwards across a busy road on a seasonal/annual basis with smaller Type 3/4 passages, then passages need to be sized according to and built at appropriate distance across the entire dispersal route, with barriers extending well beyond the end of the passages. Barriers should be robust and angled at 20-40 degrees from the road and have deflection boards.

3 If the aim is only to enable sufficient connectivity for one or a few target species to prevent severance effects according to a species-specific Population Viability Analyses, then the system should be designed only when passage use rates are sufficiently well known to satisfy the minimum viable passage use levels (MVPL) and Type 4/5 passages are placed to provide the level of calculated or estimated exchange.

This approach could be easily represented by a flow diagram in the final BMP project output.

Towards priorities; better defining mitigation systems objective

At this point of consideration, it is important to use the literature review discoveries to consider more clearly what the purpose of mitigation systems actually is. Despite many hundreds of herpetofauna road impact mitigation systems being installed in Europe and some in North America, few studies have discussed their objectives or extended beyond rudimentary evaluation of use. Noticeable, is the lack of reference to the detailed purpose of a constructed passage and barrier system, beyond the simple yet often unspoken objective of minimalizing death and injury of animals and moving as many target animals as possible back and forward through a system.

For our evaluation of passage systems constructed and studied in-situ or ex-situ, most sampled movements for relatively brief periods. We conclude that the literature reflects a general absence of definition of what mitigations systems are trying to achieve. In response to this, and with the aim of more clearly identifying how mitigation projects might fall into different categories, we can identify three approaches that might require different success/failure criteria, so that they may be judged and compared in a more qualitative and systematic way in the future and by mitigation studies.

Box 1 Shows the three principal categories of mitigation approach, as identified from this literature review findings.

The literature review suggests that only well defined, well designed and highly focused research projects can contribute to the needs and mitigation requirements for road-sensitive and fragmentation-sensitive herpetofauna species and their natural communities around the State of California. These need to relate to the development of a long-term strategy for wildlife measures in physical road construction in the State road network and for activating in parallel, where practicable and funded, a strategy towards retro-fitted defragmentation actions for damaged and degrading habitat sand species ranges.

Approach A. Multiple crossings - community mitigation

Systems with passages and barriers where the aim is for all members of the natural community, endangered and common require 'total connectivity' and the passage enables movement of the entire community, due to the importance of the habitat, species assemblage or landscape- scale movement pattern, to satisfy policy needs such as multi-species connectivity and climate change amelioration.

[Example: California Essential Habitat Connectivity Project: Linkage Design Action Plan localities].

Approach B. Single species mitigation

Systems with passages and barriers seeking to enable passage for large or significant number of individuals away from or towards a critical place of aggregation (denning, overwintering, breeding or feeding) and their return with or without juvenile cohorts in large numbers.

[Example: snakes moving away from a denning area or frogs or turtles moving from woodland to a dedicated breeding lake or wetland]. The aim is to get a large number of individuals each way through a passage at least once per year.

Note: this may be in circumstances where the formation of acceptable substitute habitat cannot be achieved on one side of a road.

Approach C. Minimum connectivity (severance avoidance) mitigation

Systems with passages and barriers where a road severs habitat that is more evenly spaced than with Approach A and where the aim is to ensure at least some future connectivity of the target species or community, to enable at least minimum continued genetic connectivity (at least one successful breeding individual crossing in each direction per generation time). This may require a critical minimum number of animals crossing to satisfy Population Viability Analysis estimates.

[Example tortoise or snake safely crossing a busy road between large expanses of desert or montane habitat.]

Box 1. The three principal categories of road impact mitigation approach, as identified from the literature review findings.

Beyond this literature review and within this CALTRANS project we have ranked the potential of negative road effects for all Californian reptile and amphibian species and identified species at highest risk of decline and extirpation from road impacts. Our program will now use the CEHC map network, along with "small landscape blocks (> $1km^2$) important for small vertebrate connectivity, to identify and prioritize DOT road segments of concern for all high and very high risk reptile and amphibian species. This information has been overlain with information relating to road size and vehicle volumes to identify areas of need as defined by threat level.

Due to the nature of funding availability, future research may need to be incorporated into experimental road mitigation designs and coordinated centrally. Ex-situ research projects may also be generated via the normal academic grant process but care must be taken because of the difficulty in relating them to real situations. Ex situ experiments still have a role to answer specific identified problems.

Existing road drainage culverts act as passages for a wide range of species and improvement of them so that dual water and wildlife passage contribution is a greater dual provision, could be a significant strategy for preventing or slowing species decline caused by roads. Further benefits may be readily achieved from adjusting existing road drainage structures to a small extent to prevent entrapment of small fauna and facilitate the use as passages.

Appendix D concerns "Thoughts, Questions and Potential Research Areas for further consideration" that will be carried forward to assist in developing research priorities and ideas to assist the programme and potentially other researchers.

6. INFORMING MANAGEMENT AND DEVELOPMENT OF BEST MANAGEMENT PRACTICES AND TECHNICAL GUIDELINES (DRAFT OUTLINE)

6.1. Introduction

In California, while substantial tracts of undisturbed habitats remain, many are bisected by roads and are present in fragmented states that may also be prone to further development pressures including road construction. Although passages and barriers for amphibians and reptiles have been constructed under and over roads in many countries and jurisdictions, including California, there has long been a need to understand what designs and materials have been effective vs. ineffective so that informed recommendations for road mitigation can be made.

Currently, Caltrans lacks the critical information and guidance to plan, design, construct and maintain cost effective wildlife passages for sensitive herpetofauna. Without appropriate guidance while planning sustainable highway facilities, Caltrans is challenged to meet its regulatory requirements and to obtain necessary permits and agreements for projects in a timely manner.

Without analysis of wildlife mitigation and connectivity options and clear decision-pathways at each stage of the process, the specification of appropriate measures may remain inadequately regulated. While some leeway must be given to project consultants and managers to determine the unique requirements of each location and circumstance, there are no standardized guidance documents or best management practices (BMPs) for amphibian and reptile passages and barriers, leaving the potential for under-performance and potential project failure. The need for more detailed guidance is clear, both in terms of system design and construction materials used and for future evaluation and refinements.

6.2 Review of BMPs

Guideline documents have been prepared to assist transportation agencies with the planning and design of measures to mitigate the impacts of roads on wildlife. As part of our literature search we compiled an extensive list of technical guidelines, best management practices (BMPs) and other guidance documents (hereafter referred to as BMPs) for mitigating impacts of roads on wildlife (Table 6.2). Many of the BMPs are in PDF and available online while few consisted of web-based content.

The objective of most BMPs, including websites, is to provide technical information on the planning and design of mitigation measures for wildlife. Many of the BMPs consist of a cursory summary of the literature and refer to case studies rather than a critical, review of current state of the science. Further, most BMPs are oriented towards large vertebrates, while there is less and more generalized information on small vertebrates, particularly amphibians and reptiles.

Table 6.2. Best management practices for mitigation road impacts on wildlife and herpetofauna.

Source	Title	Herpetofauna-specific	Herpetofauna road mitigation	General wildlife	Drainage designs
AASHTO 2007	Highway drainage guidelines	No	No	No	Yes
Arizona Game and Fish Department 2006	Guidelines for Culvert Construction to Accommodate Fish & Wildlife Movement and Passage.	No	No	Yes	No
Bissonette and Cramer 2008	Evaluation of the use and effectiveness of wildlife crossings	No	No	Yes	No
British Columbia Ministry of Forests, Lands and Natural Resource Operations 2004	Guidelines for Amphibians and Reptiles Conservation During Urban and Rural Land Development	Yes	No	No	Yes
Clayton and Bywater 2012	BMPs for Public Works Department Working within the Georgian Bay Biosphere Reserve	Yes	No	No	Yes
Clevenger 2011	Best management practices for planning considerations for wildlife passage in urban environments	No	No	Yes	No
Clevenger and Huijser 2011	Wildlife crossing structures handbook: Design and evaluation in North America	No	No	Yes	No
Federal Ministry of Transport 2000(Gemany)	Merkblatt zum Amphibienschutz an Straßen	Yes	Yes	No	No
Florida Dept of Transportation 2016	Wildlife Crossing Guidelines	No	No	Yes	No
Iuell et al. 2003	Wildlife and traffic: a European handbook for identifying conflicts and designing solutions	No	No	Yes	No
Kintsch and Cramer 2011	Permeability of existing structures for terrestrial wildlife: a passage assessment system	No	No	Yes	No
Maine Dept of Transportation 2008	Maine Waterway and Wildlife Crossing Policy and Design Guide for Aquatic Organism, Wildlife Habitat, and Hydrologic Connectivity	No	No	Yes	No
Meese et al. 2009	Wildlife Crossings Guidance Manual	No	No	Yes	No

Muller and Berthoud 1996	Fauna/Traffic Safety. Manual for Civil Engineers				
Ontario Ministry of Transportation 2006	**Amphibian Tunnel Design Review Environmental Guide for Wildlife in the Oak Ridges Moraine**	No	Yes	Yes	Yes
Ontario Ministry of Natural Resources 2013	**Reptile and Amphibian Exclusion Fencing: Best Practices**	Yes	Yes	No	No
Ontario Ministry of Natural Resources and Forests 2017	**Best Management Practices for Mitigating the Effects of Roads on Amphibian and Reptile Species at Risk in Ontario**	Yes	Yes	No	No
Righetti et al. 2008	Adapting existing culverts for the use by terrestrial and aquatic fauna	No	No	Yes	Yes
The Highways Agency 2001	Nature Conservation Advice in Relation to Amphibians	Yes	Yes	No	No
The Highways Agency 2005	Interim Advice Note 116/05. Nature Conservation Advice in Relation to reptiles and roads.	Yes	Yes	No	No
The Foundation Fieldwork Flora and Fauna 2012	VOFF/ProRail provisions for small wildlife at infrastructural works	No	No	Yes	No
U.S. Dept of Transportation 2000	Critter Crossings	No	No	Yes	No
U.S.D.A. Forest Service 2002	Wildlife Crossings Toolkit	No	No	Yes	No
VSS: Swiss Association of Road and Transportation Experts 2009	Roads and waste water management: protection measures for amphibians	Yes	Yes	Yes	Yes

6.3 Objective

The purpose of our Caltrans project is to develop BMPs based on 1) current state of knowledge of mitigation systems for herpetofauna and 2) directed research on California taxa that will improve our understanding of those systems (passage and barrier designs) to mitigate road impacts on herpetofauna

All data obtained from tasks 3-5 of our project will be used to create the BMPs. This will be done toward the end of the project (2018-2019), amassing all the information collected from review of literature and research we conduct (in-situ and/or ex-situ). The BMPs will provide much-needed information on the potential impacts of transportation projects to herpetofauna and enable well-founded decision-making regarding how best mitigate those impacts. The BMPs will aid in streamlining Caltrans projects, their planning and approval. With the BMPs in place, Caltrans will have a sound scientific basis for effective mitigation planning, policy and implementation.

We provide an outline of our proposed BMPs for amphibian and reptile species of concern in California (Table 6.2). The outline is a starting point for discussion and refinement prior to actual preparation in 2018.

The BMPs will be a relatively short, concise 40-50-page manual designed for use by Caltrans transportation staff with bullet-point text, clear graphics and easily digestible information, and easy go-to information such as hot sheets in the appendix. Particular emphasis will be placed upon making good graphic representations of crossing structure technology, including simple illustrative 3D representations so that need, purpose, and sequence of events in amphibian and reptile mitigation are readily understood by those tasked with planning and design.

Table 6.2. Proposed draft table of content for Caltrans Best Management Practices and technical guidelines for mitigating road impacts on amphibians and reptile.

Introduction
Regulatory requirements
Impacts of transportation infrastructure
    Mortality
    Connectivity
    Scales of impacts
    Mitigation of impacts
Taxonomic focus and approach
    California herpetofauna (descriptive, summary data)
    Risk analysis (brief)
Stepwise decision-making process (Flowchart?)
    Planning
    Placement
    Design: Mitigation
        Passages
            Design type
            Dimensions
            Materials
            Light
            Humidity
            Temperature
            Substrate
            Maintenance
        Barriers
            Design type
            Dimensions
            Materials
            Maintenance
    Performance assessment
        Study design
        Methods

Appendix
- Hot sheets for each herpetofauna guild (Frog, Salamander, Lizard, Aquatic snake, Terrestrial snake, Toad, Tortoise, Turtle)
- Hot sheets for Passages and Barriers (Passage Type 1-5, Barriers)
- Summary of passage findings from literature for CA species
- Summary of barrier findings from literature for CA species

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APPENDICES

APPENDIX A

List of species – common and scientific name

APPENDIX B

Data inputted from sources for literature review

APPENDIX C

Evaluation of source information strength and coverage

APPENDIX D

Thoughts, questions and potential research areas for further considerations

APPENDIX A

List of species – common and scientific name

AMPHIBIANS	

FROGS	**28 Taxa**
Common name	**Scientific name**
agile frog	*Rana dalmatina*
broad-palmed frogs	*Litoria latopalmata*
bullfrog	*Lithobates catesbeianus*
common frog	*Rana temporaria*
copper-backed brood frog	*Pseudophryne raveni*
edible frog (water frog group)	*Pelophylax kl. esculentus*
Gray treefrog	*Hyla versicolor*
green and golden bell frog	*Litoria aurea*
green frog	*Rana clamitans*
green treefrog	*Hyla cinerea*
growling grass frog	*Litoria raniformis*
leopard frog	*Rana pipiens*
moor frog	*Rana arvalis*
red-legged frog	*Rana aurora*
striped marsh frog	*Limnodynastes peronei*
marsh frog	*Pelophylax ridibundus*
mink frog	*Lithobates septentrionalis*
northern green frog	*Rana clamitans melanota*
northern banjo frog	*Limnodynastes*
northern leopard frog	*Lithobates pipiens*
ornate burrowing frog	*Platyplectrum ornatum*
pig frog	*Lithobates grylio*
pine woods treefrog	*Hyla femoralis*
southern leopard frog	*Lithobates sphenocephalus*
southern cricket frog	*Acris gryllus*
squirrel treefrog	*Hyla squirella*
striped marsh frog	*Limnodynastes peronii*
wood frog	*Lithobates sylvaticus*

Common name	**Scientific name**
TOADS	**9 Taxa**
American toad	*Anaxyrus americanus*
Cane toad	*Rhinella marina*
common toad	*Bufo bufo*
eastern American toad	*Bufo americanus americanus*
eastern narrow-mouthed toad	*Gastrophryne carolinensis*
eastern spadefoot toad	*Scaphiopus holbrookii*

western toad	*Anaxyrus boreas*
southern toad	*Anaxyrus terrestris*

Common name	Scientific name
SALAMANDERS	**13 Taxa**
red-backed salamander	*Plethodon cinereus.*
California tiger salamander	*Ambystoma californiense*
great crested newt	*Triturus cristatus*
greater siren	*Siren lacertina*
Idaho giant salamander	*Dicamptodon aterrimus*
long-toed salamander	*Ambystoma macrodactylum*
northern red salamander	*Pseudotriton ruber ruber*
Rough-skinned newt	*Taricha granulosa*
Santa Cruz long-toed salamander	*Ambystoma macrodactylum croceum*
smooth newt	*Lissotriton vulgaris*
spotted salamander	*Ambystoma maculatum*
tiger salamander	*Ambystoma tigrinum*
two-toed amphiuma	*Amphiuma means*

REPTILES	

SNAKES	33 Taxa
black swampsnake	*Seminatrix pygaea*
brownsnake	*Storeria victa*
common gartersnake	*Thamnophis sirtalis*
common kingsnake	*Lampropeltis getula*
copperbelly water snake	*Nerodia erythrogaster neglecta*
cornsnake	*Pantherophis guttatus*
cottonmouth	*Agkistrodon piscivorus*
dugite	*Pseudonaja affinis*
eastern brown snake	*Pseudonaja textilis*
eastern racer	*Coluber constrictor*
eastern ribbon snake	*Thamnophis sauritus*
eastern garter snake	*Thamnophis sirtalis*
Florida green watersnake	*Nerodia floridana*
gophersnake	*Pituophis catenifer catenifer*
ladder snake	*Rhinechis scalaris*
latastes viper	*Vipera latastei*
massassauga rattlesnake	*Sistrurus catenatus*
midland water snake	*Nerodia sipedon*
milksnake	*Lampropeltis triangulum*
Mohave rattlesnake	*Crotalus scutulatus*
Montpellier snake	*Malpolon monspessulanus*
northern water snake	*Nerodia sipedon*

red-bellied mudsnake	*Farancia abacura*
ribbonsnake	*Thamnophis sauritus*
ring-necked Snake	*Diadophis punctatus*
rough greensnake	*Opheodrys aestivus*
sidewinder	*Crotalus cerastes*
smooth green snake	*Opheodrys vernalis*
southern watersnake	*Nerodia fasciata*
western diamondback rattlesnake	*Crotalus atrox*
western patch-nosed Snake	*Salvadora hexalepis*
yellow-faced whip snake	*Demansia psammophis*
yellow ratsnake	*Elaphe obsoleta quadrivittata*

LIZARDS	**35 taxa**
Argentine black and white tegu	*Salvator merianae*
Asian house gecko	*Hemidactylus frenatus*
bar-sided forest-skink	*Eulamprus tenuis*
Burton's snake lizard	*Lialis burtonis*
common blue-tongue lizard	*Tiliqua scincoides*
copper tail skink	*Ctenotus taeniolatus*
desert Spiny Lizard	*Sceloporus magister*
dubious gecko	*Gehyra dubia*
dunes sagebrush lizard	*Sceloporus arenicolus*
eastern stone gecko	*Diplodactylus vittatus*
eastern bearded dragon	*Pogona barbata*
eastern striped skink	*Ctenotus robustus*
elegant Snake-eyed Skink	*Cryptoblepharus pulcher*
flat-tailed horned lizards	*Phrynosoma mcalli*
friendly skink	
Galápagos lava lizards	*Microlophus albemarlensis.*
garden skink	*Lampropholis guichenoti*
gila monster	*Heloderma suspectum*
green anole	*Anolis carolinensis*
Iberian wall lizard	*Podarcis hispanica*
large psammodromus	*Psammodromus algirus*
lively skink	*Carlia vivax*
long-nosed leopard lizard	*Gambelia wislizenii*
ocellated lizard	*Timon lepidus*
rainbow skink	*Lampropholis delicata*
regal horned lizard	*Phrynosoma solare*
robust skink	*Cyclodina alani*
sagebrush lizard	*Sceloporus graciosus*
scute-snouted calyptotis	*Calyptotis scutirostrum*
tiger whiptail	*Aspidoscelis tigris*

tommy roundhead dragon	*Diporiphora australis*
tree-base litter-skink	*Lygisaurus foliorum*
western banded gecko	*Coleonyx variegatus*
western bobtail lizard	*Tiliqua rugose rugosa*
zebra-tailed Lizard	*Callisaurus draconoides*

TURTLES	**5 taxa**
Blanding's turtle	*Emydoidea blandingii*
eastern box turtle	*Terrapene carolina carolina*
painted turtle	*Chrysemys picta*
snapping turtle	*Chelydra serpentina*
spotted turtle	*Clemmys guttata*

TORTOISES	**2 taxa**
desert tortoise	*Gopherus agassizii*
Hermann's tortoise	*Testudo hermanni*

APPENDIX B

Data inputted from sources for literature review

Source	Literature reference
Source location	L = library web database searches, CSB = CSB already had article, LC = literature cited, RER = Road Ecology reference
World zone	NAM, EUR, ASIA, LAM, AUST, AFR
Country	Country
Location	State/Province
Specific Location	City
Road type	(2) 2-lane, (4) 4-lane,
Traffic volume	if reported.
HabitatGen	Desert (D), forest (F), grassland (G) scrub (S) riparian (R) wetland (W) agriculture (A)
Taxa	L = lizard, TS = terrestrial snake, AS= aquatic snake, F = frog, T = toad, SA= salamander, Tu = turtle, reptile, To = tortoise, M = Mammal, R = unspecified, A = unspecified amphibian
CA Taxa?	Y, N
Species	if in CA
Obj?	Study objective
No. CS	State number crossing structures (CS) used in study: 1, 2, 3, 4 …
Dist. betw. CS	Distance between CS (m)
Method	O = Observations, P= Pitfall, C= Cameras, M&R = Mark and recapture TE=Telemetry , TR=Trackpad, PT=PIT tag
Duration	Number of months
CS type	Engineered (E), non-engineered (NE) (i.e. designed for wildlife movement=E vs culvert=NE)
CS Design	Type 1-5: Type 1: Mountain tunnels and green bridges (general) Type 2: Open bridges and viaducts Type 3: Smaller road underpasses under 60 ft/20 metres Type 4: Water culverts under 10 ft / 3 metres Type 5: Micro underpasses < 3 ft/1.0 m diameter/span

CS Length	(m)
CS Width	(m)
CS Height	(m)
CS materials	Conc = concrete, MCSP=metal CSP, plastic, PC = polymer concrete
Bottom Natural Substrate	Y/N
CS depth	At grade (AG), below grade (BG) over grade (OG)
Fencing (F)?	Yes/No
F_Design	(O) One-way/curved (V) vertical (OH) with overhang
F_Length (m)	Length (total, end to end)
F_Height(m)	height above ground
F_Dim_other	DB x OH size overhang (mm) x depth below ground
F_Materials	Concrete, MCSP = Metal Corrugated Steel, MM-Metal Mesh, SP = solid plastic 2mm-10 mm, cloth, lumber PC = Polymer concrete, PM= Plastic mesh/shade, PO = Polythene, PL + pressure-treated
Study design	Tunnel Usage, BACI, CI, anecdotal, other
Variables	None, moisture, light, noise, predators, internal structure, ledges
Recommendations	Y, N
Publication status	P= peer review (journal article), U =unpublished report/manuscript, A=anecdotal/online source
In situ/ ex situ	In situ- culvert under road, etc. ex situ experimental in habitat
Conclusions	Summarize main findings

APPENDIX C

Evaluation of source information strength and coverage

SNAKES

1. PASSAGE CONSTRUCTION & USE

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Ascensao and Mira 2007	Portugal	Not stated	NA	0.8-1.0 m	8-37 m	NA	Tendency towards use of shorter passages
Bager & Fontoura 2013	Brazil	Not stated	NA	1.6	ca 25 m	NA	Slight decline in road mortality after passages & barriers installed.
Baxter-Gilbert et al. 2015	Canada	Eastern garter snake, Northern watersnake	450–600 m	Two 3.4 m x 2.4 m with flooded median area.	c. 63 m: 2 x 24.1 m + fenced 15.3 m gap through the median	Concrete box culverts	BACI approach was attempted. Recorded use of passage very low. Use of passages is compromised if barriers do not work.
Chambers and Bencini 2015	Australia	Dugite	NA	4 x sites 10 passages. Round & rectangular 900 mm-1.2 m	23-68 m	Unstated – concrete?	Single use of one passage
Bellis et al. 2013	USA	Not stated	Two bridge overpasses 600 m apart	and drain culvert 1.65m	124 m	NA	Structures may not have been effective in reducing mortality

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Passage Length	Passage material	Conclusions
Dodd et al. 2004	USA	Cottonmouth Eastern Racer Ring-necked Snake Cornsnake Yellow Ratsnake Red-bellied Mudsnake Milksnake Southern Watersnake Florida Green Watersnake Rough Greensnake Black Swampsnake Brownsnake Eastern Ribbonsnake Common Gartersnake	200-500m	Box Two of 2.4 x 2.4 m Two of 1.8x1.8 m Round Four of 0.9 m	44 m	Concrete	Mortality reduced and use of passages generally increased after fitting barriers.
Eads 2013	USA	Ribbonsnake Gartersnake	NA	0.33, 0.66, 1.0, & 1.33 m	5-10 m	NA	Larger culverts encouraged higher crossing rates than smaller culverts. Best culvert design is one with widths of at least 1.33 m, with either water or soil as the substrate.
Gunson 2015	Canada	Massassauga Rattlesnake Milksnake Ribbonsnake Eastern Gartersnake Northern Watersnake Brownsnake Smooth Green snake Ring-necked snake Unidentified snake	Single culvert	Round 800 mm	Ca. 19 m	Corrugated Metal Culvert	Snakes entered passages but immediately turned back.

Colley et al. 2017	Canada	Massassauga Rattlesnake Garter snake	2 pairs <300m, N.R	Height 50-60 cm	8.9 m	Concrete with open grates	4 culverts monitored and used by both Massasaugas and garter snakes. 14 Massasuaga recorded in passages over 2-year period

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Passage Length	Passage material	Conclusions
Grandmaison 2011	USA	Western Diamond-backed Rattlesnake Sidewinder Mohave Rattlesnake Common Kingsnake Gophersnake Western Patch-nosed Snake	NA	Round 24-36 inch CMC Box	2-4 lane Est 20-40 metres.	Corrugated Metal Culvert Concrete Box Culvert	2,354 culverts studied. Snakes used all passage sizes snake passage rates were highest for box culverts with little difference between the CMP-style culverts
Rodriguez et al. 1996	Spain	Ladder snake Montpellier snake Latastes viper	Highly variable	4 types 1.2-6.0 m	13-64 m	Concrete	Note rail not road; culverts, underpasses and flyovers. Reptiles (snakes and lizards grouped) preferred passages of intermediate size,

Veage & Jones 2007 McGregor et al. 2015 (Both Compton)	Australia	Yellow-faced whip snake Eastern brown snake snake	NA	Overpass Hourglass shape. End widths20m Mid-width 10 m Two box culvert underpasses 2.4 m high, 2.5 m wide 3 x ca.3m stormwater culverts	Overpass 70 m Box culvert 48 m Stormwater Culverts circa 48 ? m	Habitat	Yellow-faced whip snake resident on or a regular visitor to the overpass.

2. SNAKES PASSAGE ENVIRONMENT

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Ascensao & Mira 2007	NA	NA	NA	NA	NA	NA	
Bager & Fontoura 2013	NA	NA	NA	NA	NA	NA	
Baxter-Gilbert et al. 2015	NA	NA	NA	Flooding occured	NA	NA	
Bellis et al. 2013	NA	NA	NA	NA	NA	NA	
Chambers and Bencini 2015							
Dodd et al. 2004	NA	NA	NA	NA	NA	NA	

Eads 2013	See wetness	NA	NA	Smaller water snakes move faster & more often through a wet culvert than one with just soil.	NA	NA	Smaller water snakes move faster & more often through a wet culvert than one with just soil.
Gunson 2015	NA	NA	NA	All snakes entering a part-waterlogged passage rapidly turned back for unknown reason	NA	A beaver screen was placed across the culvert ends.	Turn backs considered possibly temperature or predator risk-related.
Colley et al. 2017							
Grandmaison 2011	Trend for higher passage rates in culverts with a greater amount of natural substrate.	Trend for higher passage rates in culverts with higher openness ratios	NA	NA	NA	NA	Concrete box culverts identified as most effective structure for snakes in the Sonoran Desert.

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Rodriguez et al. 1996		NA	Reptiles moved between sun-warmed and shaded vertical surfaces for thermoregulation.	NA	NA	NA	Crossing rate higher where suitable habitat exists nearby.
Veage and Jones 2007 McGregor et al. 2015 (Both Compton)	NA	NA	NA	NA	NA	NA	Natural habitat passage avoids confined space issues.

3. SNAKES BARRIERS

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Ascensao & Mira 2007	NA	NA	NA	NA	
Bager & Fontoura 2013	1.3 m	NA	0.4 m	Concrete base 0.2 m above ground buried depth of 0.4 m. Lower portion 0.65 m high, is square, 50 mm mesh. Upper portion of fence is 100 mm mesh 0.45 m high.	Barrier may not have worked for most species ?
Baxter-Gilbert et al. 2015	0.8 m	NA	0.2 m with 10 mm wide buried lip. Fixed to base of 2.3 m chain-link mammal fence	Heavy-gauge plastic textile	An increase in the percentage of snakes detected dead on the road post-mitigation, suggesting that the fencing was not effective.
Bellis et al. 2013	2.5 m	NA	NA	Chainlink	Barrier may not have worked for many species ?
Chambers and Bencini 2015					
Dodd et al. 2004	1.1 m wall has152 mm overhang Also: Standard fence with 2 guard rails (one on top of the other)	NA	NA prob 1.0 m + Standard has hardware cloth barrier below ground	Concrete	Mortality almost completely removed by placement of 1.1 m barrier. Standard fence does not work well and requires a 20cm underground metal component to reduce mvt underneath.
Eads 2013	NA	NA	NA	NA	Tree canopy overhang may influence crossing frequency.

Gunson 2015	Est 1.2 m	Ext 700mm	NA	Plastic cloth/sheeting	Plastic cloth is not very durable. Installation challenging when culvert is part submerged.

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Colley et al. 2017	Canada	Massassauga Rattlesnake Garter snake	30 cm	Light-gauge metal hardware cloth (1 cm gauge mesh)	Required continual labor intensive monitoring and repair. Not recommended as long term solution. Had to extend length due to roadkill at ends. Smaller species got through large mesh. Road mortality was reduced.
Grandmaison 2011	42 inches		6 inches below	-Rusticated Steel Flashing -Concrete Panel -Concrete Panel with 4-inch Overhang -2 sections Guard Rail	Snakes were capable of negotiating vertical barriers if the barriers were shorter than the snakes length. The most effective design for funnelling snakes to culverts was the guard rail barrier.
Rodriguez et al. 1996	NA	NA	NA	NA	Barriers fitted after a period of study did not change passage use rates.

Veage and Jones 2007 McGregor et al. 2015 (Both Compton)	2.48 m metal mesh with UV stabilised PVC sheeting 10 mm thick and 480 mm high at base of the fence. Plus metal sheet on forest side – see materials.		Extends to just below ground level.	Single metal sheet strip 590 mm high attached to the fence 1.38 m above the ground on the forest side to prevent animals climbing.	The barrier design appears to have been effective in keeping animals on the overpass.

2. TORTOISES

1. TORTOISE PASSAGE CONSTRUCTION & USE

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Ruby et al. 1994	USA	Desert tortoise	NA	Rectangular 2.44 x 1.22 m Also ex-situ Experiment 100-290 cm diam	70 m 900-2,800 mm long	Concrete PVC pipe	Tortoises willingly entered concrete culverts under large highways. Tortoises left captive pen via short PVC pipes.
Boarman and Sazaki 1996	USA	Desert tortoise	NA	900-1500 mm 1,400 mm 3.0-3.6 m x 1.8-3.0 m	33-66 m	Corrugated steel pipe Concrete Box concrete	24 culverts. 3 bridges Pit tags used to monitor population near 3 culverts. Over 6 months 2 tortoises used culverts ten times.
Guyot and Clobert 1997	France	Hermann's tortoise	One road tunnel and two culverts	NA	NA	NA	284 displaced tortoises excluded from 40 Ha habitat & marked and released. No passage use recorded.
Boarman et al. 1998	USA	Desert Tortoise	N.R.	1.6m	66m	Corrugated metal pipe	4 tortoises passed through on 60 occasions 1994-95. Metal aprons were installed at culvert entrances.

2. TORTOISES PASSAGE ENVIRONMENT

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Ruby et al. 1994	NA	NA	NA	NA	NA	NA	Tortoises seem to use bare passages but may return to entrance point after resting.
Boarman and Sazaki 1996	NA	NA	NA	NA	NA	NA	
Guyot and Clobert 1997	NA	NA	NA	NA	NA	NA	

3. TORTOISES BARRIERS

Source	**Barrier Height (maximum)**	**Barrier Height (minimum)**	**Barrier buried (depth)**	**Barrier materials**	**Conclusions**
Ruby et al. 1994	1000 mm	200 mm	Varies	Log cabin, Railroad ties, Chain link, Chicken wire, Corral slat fence wood, Aluminum flashing, Silverized insulation, Mesh (1 cm), buried, Mesh (1 cm), not buried, Trench with mesh, Trench with PVC pipe, Cement block, Telephone poles.	Solid barriers are most effective but 10mm hardware cloth fences are just as effective. Tortoises can see through cloth which does not accumulate as much wind-blown sand as solid barriers. Tortoises tend to walk away rather than along solid barriers. Tortoises disturbed by visual, vibration & noise stimuli from highway traffic on the other side of solid concrete barrier. A tortoise's response to shadows, or heavy vibration from trucks was to stop moving (8 of 10 animals) & in most cases withdraw the head into the shell. When several trucks passed in convoy, tortoise withdraws completely into shell. Vibration or noise alone without visual stimuli also provoked defensive responses.

Boarman and Sazaki 1996	450 mm 24 km length		150mm	1.3 cm mesh galv steel hardware cloth on 6-strand wire fence on bar uprights	New and properly maintained fencing is very effective as a barrier for tortoises
Guyot and Clobert 1997	400 mm		100 mm	Sheep wire fence + additional fine wire mesh covering	The mortality rate due to traffic was considered very low.

3. LIZARDS

1. LIZARD PASSAGE CONSTRUCTION & USE

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Ascensao and Mira 2007	Portugal	Not stated	NA	0.8-1.0 m	8-37 m	NA	Tendency towards use of shorter passages
Bager and Fontoura 2013	Brazil	Argentine black and white tegu	NA	1.6	ca 25 m	NA	Slight decline in road mortality after passages & barriers installed.
Chambers and Bencini 2015	Australia	Western bobtail lizard Southern Heath monitor Gould's sand monitor Western bluetongue	NA	4 x sites 10 x passages. Round & rectangular 900 mm-1.2 m	23-68 m	Unstated – concrete?	Bobtail lizard used all passages & southern heath monitor lizard used several of them. Recommends dividing longer passages via use of vegetated median to shorten passage length and to increase crossing frequency.
Dodd et al. 2004	USA	Green Anole	200-500m	Box -Two of 2.4 x 2.4 m -Two of 1.8x1.8 m Round -Four of 0.9 m	44 m	Concrete	Observed use.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Grandmaison 2011	USA	Tiger Whiptail Zebra-tailed Lizard Western Banded Gecko Long-nosed Leopard Lizard Gila Monster Regal Horned Lizard Desert Spiny Lizard	NA	Round 24-36 inch CMC Box ?	2-4 lane Est 20-40 metres.	Corrugated Metal Culvert Concrete Box Culvert	Greatest level of permeability will be achieved using concrete box culverts compared to 24- or 36-inch CMP culverts
Hibbitts et al. 2016	USA	Dunes sagebrush lizard	NA	1000 high x 200 mm deep	Ca 5 m	Open trench	Experiments indicating species may avoid crossing narrow dirt tracks or trench across track.
Painter and Ingraldi 2007	USA	Flat-tailed horned lizard		24-inch diameter steel culverts, 36-inch diameter steel culverts, 4-foot tall by 8-foot wide box culverts.	40 feet	Steel pipe and concrete box culverts	Six culverts of three dimensions and two interior lighting options. Flat-tailed horned lizards can use culverts as road crossing structures, but the evidence did not reveal a strong selection for or against any culvert type.
Rodriguez et al. 1996	Spain	Ocellated lizard Iberian wall lizard Large psammodromus	Variable	4 types 1.2-6.0 m	13-64 m	Concrete	

Veage and Jones 2007 McGregor et al. 2015 Both Compton site	Australia	Asian house gecko Common blue-tongue lizard Bar-sided forest-skink Burton's snake lizard Elegant Snake-eyed Skink Copper tail skink Eastern striped skink Friendly skink Garden skink Lively skink Rainbow skink Robust skink Tree-base litter-skink Unidentified skink Tommy roundhead dragon (breeding) Dubious gecko Eastern stone gecko Wood gecko Scute-snouted calyptotis Eastern bearded dragon	NA	Overpass Hourglass shape. End widths20m Mid-width 10 m Two box culvert underpasses 2.4 m high, 2.5 m wide 3 x ca.3m stormwater culverts	Overpass 70 m Box culvert 48 m Stormwater Culverts circa 48 ? m	Habitat	Lizards are using the habitat of the structure as an extension of the naturally occurring forest within the surrounding reserve. Only one recorded forest specialist, D. vittatus, was not recorded on the overpass.

2. LIZARD PASSAGE ENVIRONMENT

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Ascensao and Mira 2007	Portugal	NA	NA	NA	NA	NA	
Bager and Fontoura 2013	Brazil	NA	NA	NA	NA	NA	
Chambers and Bencini 2015	Australia			NA	NA	See conclusions	For bobtail lizard, amount of vegetation cover negatively affected the proportion of the lizard population using the underpass.
Dodd et al. 2004	USA	NA	NA	NA	NA	NA	
Grandmaison 2011	USA	NA	NA	NA	NA	NA	
Hibbitts et al. 2016	USA	NA	NA	NA	NA	NA	
Painter and Ingraldi 2007	USA	One of each type of passage was lit with skylights	Passages were slightly cooler than the outside temperature	NA	NA	NA	Of 54 flat-tailed horned lizards tested 12 completed the crossings. The 36-inch culvert without skylights was used 5 times. The 24-inch diameter culvert with skylights was not used, and other culvert designs were each used once or twice.
Rodriguez et al. 1996	Spain	NA	Lizards moved between sun-warmed & shaded vertical surfaces for thermoregulation	NA	NA	NA	Crossing rate was higher where suitable habitat exists nearby passage entrances.

McGregor et al. 2015 Veage and Jones 2007 Compton	Australia	NA	NA	NA	NA	NA	Natural vegetation appears to enable high use levels

3. LIZARD BARRIERS

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Ascensao and Mira 2007	NA	NA	NA	NA	
Bager and Fontoura 2013	1.3 m	NA	0.4 m	Concrete base 0.2 m above ground buried depth of 0.4 m. Lower portion 0.65 m high, is square, 50 mm mesh. Upper portion of fence is 100 mm mesh 0.45 m high.	Barrier may not have worked for most species ?
Chambers and Bencini 2015	1800 mm	600mm	at least 300 mm	?	
Dodd et al. 2004	NA	NA	NA	NA	
Grandmaison 2011	42 inches	NA	6 inches below	-Rusticated Steel Flashing -Concrete Panel -Concrete Panel with 4-inch Overhang -2 sections Guard Rail	The most effective designs for funneling lizards to underpass structures are concrete panels with a 4-inch overhang, rusticated steel, and guard rail barriers. Steel with overhang may work as well.
Hibbitts et al. 2016	NA	NA	NA	NA	
Painter and Ingraldi 2007	NA	NA	NA	NA	
Rodriguez et al. 1996	NA	NA	NA	NA	Barriers fitted after a period of study did not change passage use rates.
Veage and Jones 2007 McGregor et al. 2015 Both Compton Site.	NA	NA	NA	NA	Suggestions are that the barriers are effective for lizards.

4. TURTLES

1. TURTLE PASSAGE CONSTRUCTION

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Aresco, 2005	USA	Chicken turtle Eastern box turtle Eastern mud turtle Florida cooter Florida softshell Gopher tortoise Stinkpot Snapping turtle Suwannee cooter Yellow-bellied slider	NA	3.5 m	46.6m	Steel	Some evidence of culvert use by turtles. More culverts required.
Bager & Fontoura 2013	Brazil	Hilaire's side-necked turtle Black spine-neck swamp turtle Argentine snake-necked turtle	NA	1.6	ca 25 m	NA	Slight decline in road mortality after passages & barriers installed.
Baxter-Gilbert et al. 2013	Canada	Snapping turtles Blanding sturtles Painted turtles	450–600 m	Two 3.4 m x 2.4 m Flooded median area.	c. 63 m: 2 x 24.1 m + fenced 15.3 m gap at the median	Concrete box culverts	
Bellis et al. 2013	USA	Not stated	NA	1.65m	124 m	NA	Structures may not have been effective in reducing mortality
Caverhill et al. 2011	Canada	Snapping turtle Blanding's turtle	NA	1.8 m	25 m	Corrugated steel	Both turtle species swam through aquatic passage during the daytime May-October.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Dodd et al. 2004	USA	Snapping Turtle Striped Mud Turtle Unidentified Mud Turtle Florida Red-bellied Turtle	200-500m	Box Two of 2.4 x 2.4 m Two of 1.8x1.8 m Round Four of 0.9 m	44 m	Concrete	Mortality reduced and use of passages generally increased after fitting barriers.
Gunson 2015	Canada	Snapping turtle Painted turtle	Single culvert	Round 800 mm	Ca. 19 m	Corrugated Metal Culvert	Adult turtles were prevented from entering the study passage by placement of a beaver screen
Gunson 2017	Canada	Snapping turtle Painted turtle Blanding's turtle	Varies	1.5 m round culverts Box culverts 1.2 x 1.8 3.3w x 2.8h		Concrete	Small numbers of painted and snapping turtles but not Blanding's turtles were recorded in passages using camera sampling from June each year.
Hagood and Bartles 2008	USA	Eastern box turtle	NA	2 culverts 380 mm 530 mm	Not stated 10-20 m ?	Not stated	Three individuals recorded entering and moving in both directions in culvert

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Lang 2000	USA	Blanding's turtle	NA	36 " round 48" round 42" arch	Under 10 metres	Metal	Blandings turtles will use 36-48 inch passages
Langen 2011	USA	Snapping turtle Painted turtle Blanding's turtle	NA	1.3 m diameter	20-25 m est.	Corrugated metal half flooded	Radio telemetry of a small no of snapping turtle individuals showed some turtles did cross using the culverts
Sievert and Yorks 2015	USA	Blanding's turtle Spotted turtle Painted turtle	NA Ex situ experiments	Apertures of 600 x 600 mm 1200 x 1200 mm and 1.2 x 2.4 m and 'at grade' and 'below grade' positions.	12.0 m and 24 m	Plywood with soil/gravel base	Passage size and light levels have an influence on the level of use and speed of crossing for turtles, the extent of which varies between species.
Woltz et al. 2008	USA	Snapping turtle Painted turtle	NA	diameters 300mm, 500m m, 600 mm, and 800 mm, lined with site soils.	4 x 3.0 m, one 6.1 m, and one 9.1m in length.	corrugated black PVC (polyvinyl chloride) pipes,	Turtles preferred larger diameter tunnels (>0.5 m) whereas painted turtle preferred tunnels of intermediate (0.5–0.6 m) diameter. Painted turtles showed non-random choice of different lengths of tunnel, possibly indicating some avoidance of the longest tunnel (9.1 m)

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Aresco, 2005	NA	NA	NA	NA	NA	NA	
Bager & Fontoura 2013	NA	NA	NA	NA	NA	NA	
Baxter-Gilbert et al. 2013	NA	NA	NA	Flooding occured	NA	NA	
Bellis et al. 2013	NA	NA	NA	NA	NA		
Caverhill et al. 2011	Half flooded permanently	NA	NA	Half flooded permanently	NA	NA	Flooded passages work to some degree for these two species
Dodd et al. 2004	NA	NA	NA	NA	NA	NA	Some use indicated
Gunson 2015	NA	NA	NA	Passage part flooded	NA	A beaver screen was placed across the culvert ends.	
Gunson 2017	NA	NA	NA	NA	NA	NA	Some use indicated
Hagood and Bartles 2008	NA	NA	NA	NA	NA	NA	
Lang 2000	NA	NA	NA	NA	NA	NA	
Langen 2011	NA	NA	NA	Passage part flooded	NA	NA	Some use indicated

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Sievert and Yorks 2015	Natural	Varied passage light levels using natural (open top) and artificial (light bulbs).	NA	NA	Variations tried. Did not influence mvt rate into passage from release pen area	NA	Passage light levels and barrier transparency play a significant role in passage use by turtles. Lighting at the Median only did not appear to increase crossings.
Woltz et al. 2008	sections lined with concrete, soil, gravel, or bare PVC.	four sections 600 mm diameter; 3.0-m-long pipe with overhead punctures of 0%, 0.65%, 1.3%, or 4.0% of the pipe's c/s surface area,	NA	NA	NA	NA	No evidence of preference for substrate or light.

3. TURTLE BARRIERS

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Aresco, 2005	400 m	NA	200 mm	woven vinyl erosion control fencing	Turtle mortality before installation of the fence (11.9/km/day) was significantly greater than post-fence mortality (0.09/km/day) and only 84 of 8,475 turtles climbed or penetrated the drift fences.
Bager & Fontoura 2013	1.3 m	NA	0.4 m	Concrete base 0.2 m above ground buried depth of 0.4 m. Lower portion 0.65 m high, is square, 50 mm mesh. Upper portion of fence is 100 mm mesh 0.45 m high.	Poor system design limits effective outcomes.
Baxter-Gilbert et al. 2013	0.8 m	NA	0.2 m with 10 mm wide buried lip. Fixed to base of 2.3 m chain-link mammal fence	Heavy-gauge plastic textile	We found no difference in abundance of turtles on the road between un-mitigated & mitigated highways, and an increase in the % of turtles DOR post-mitigation, suggesting that the fencing was not effective.
Bellis et al. 2013	2.5 m	NA	NA	Chainlink	Barrier may not have worked for many species
Caverhill et al. 2011	Ca 500mm	NA	Buried but unclear how deep	Black plastic temporary	Reported as effective

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Dodd et al. 2004	1.1 m wall has152 mm overhang Also: Standard fence with 2 guard rails (one on top of the other)	NA	NA prob 1.0 m + Standard has hardware cloth barrier below ground	Concrete	Mortality almost completely removed by placement of 1.1 m barrier. Standard fence does not work well and requires a 20cm underground metal component to reduce movement underneath.
Gunson 2015	Est 1.2 m with some localised Animex fencing.	Ext 700mm	NA	Plastic cloth/sheeting	Barriers need to be long enough and strong enough to be effective
Gunson 2017	800 mm	NA	200 mm with 10 mm lip running perpendicular underground	heavy-gauge plastic textile fixed to the base of the 2.4 m tall large animal mesh wire fencing	Barrier was effective in preventing road mortality but may only last a further five years.
Hagood and Bartles 2008	Unclear	NA	Unclear	Pre-staked plastic erosion material	Reported to have worked effectively over 5 months
Lang 2000	18 inches	NA	NA	Chicken wire and lathe	Appeared to function.

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Langen 2011	3 fence types all 600 mm high	600 mm	The base of the wire fence was buried 50 mm into the ground with one fence and flush with the other. The wooden slats were buried 100mm into the ground.	-Wood slat barrier. -Vinyl coated metal wire mesh barrier 600 mm high, 25 x 25 mm mesh on light fence posts with 300mm mesh, 6 x 6 mm. -12 gauge vinyl-covered wire 600 mm high, 50 x 100 mm mesh on posts flush with the road & top of fence flush with guardrail.	The 25 x 25 mm mesh vinyl-coated steel fencing fixed to light-duty fence posts, with UV-resistant cable ties and buried up to 100 mm is effective in stopping turtle movement & should be at least 600 mm high, ideally with a small lip at the top.
Sievert and Yorks 2015	900 mm	NA	NA	20 gauge 32 mm mesh galvanized chicken wire attached to wood stakes, one open and one covered with black plastic sheet.	Barrier opacity influences turtle response and so can be used according to system design.
Woltz et al. 2008	four heights of barriers 300 mm, 600 mm and 900 mm	300	NA	corrugated plastic fences on wood posts	Fences 300 mm and 600 mm in height were effective barriers to snapping turtle and 600 mm and over for painted turtle..

5. FROGS

1. FROGS PASSAGE CONSTRUCTION & USE

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Bellis et al. 2013	USA	Not stated	NA	1.65m	124 m	NA	
Brehm 1989	Germany	Common frog Edible frog Moor frog	Four study sites. One with passage study	200-1000mm	10-18 m	Corrugated iron Concrete Polymer concrete	Species use of passage varied from around 20% to higher levels (but small sample size). Main issue is individuals not locating passage entrance.
Cunnington et al. 2014	Canada	Bullfrog Gray treefrog Mink frog Northern green frog Northern leopard frog Wood frog	Varied	rectangular culverts of 100–200 cm	Ca 15 m est.	concrete	Presence of road drainage culverts does not reduce road mortality but fencing does.
Dodd et al. 2004	USA	American bullfrog Green treefrog Green frog Pig frog Pine woods treefrog Southern leopard frog Southern cricket frog Squirrel treefrog	200-500m	Box Two of 2.4 x 2.4 m Two of 1.8x1.8 m Round Four of 0.9 m	44 m	Concrete	Mortality reduced and use of passages generally increased after fitting barriers.
Fitzsimmons and Breisch 2015	USA	Unstated 5 frog species present	46 m	Box culvert 1.5x 1.5 m	11 m	concrete	Passage used to some extent by 3 of 5 frog species

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Gunson 2015	Canada	Green frog Northern Leopard frog	Single culvert	Round 800 mm	Ca. 19 m	Corrugated Metal Culvert	Unclear if small number of frogs entered passage
Hammer et al. 2014	Australia	Broad-palmed frogs Green and golden bell frogs Striped marsh frogs	NA	500 w× 320h mm.	12.0 m	Polymer concrete	Tropical frogs appear to react to passages in a different way to temperate frogs and showed little interest in moving through passage under controlled conditions.
Koehler and Gilmore 2014	Australia	Growling grass frog	NA	Four 2.4 m wide x 1.2 m high	20 m	Concrete box culverts	Around 30% + of sample of individuals recorded (mark & recapture) moving more than once through passages, included swimming through flooded culverts during in-situ habitat /species relocation project.
Krikowski 1989	Germany	Common frog	Under 100 m	Three 400 mm One 600 mm	13-19 m 26 m	Concrete pipes	Large numbers of migrating medium sized frogs may be moved under a road using 400-600 mm passages using the 'compulsory' one-way passage system.
Lesbarreres et al. 2004	France	Agile frog Edible frog	NA	500 mm	2.0 m	Concrete	Species may differ in their preferences & in their likelihood of using underpasses when given a choice.

Malt 2012	Canada	Red-legged frog	NA	8 culverts: 1 m PVC 2 m Conc 3 m CSP	Varies: 21.0 -37.0 metres.	Corrugated steel pipe. Plastic PVC Concrete	Only 9% of anurans were observed on camera passing through culverts with many escaping onto the road due to barrier deficiences.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Merrow 2007	USA	Wood frogs	NA	-176 m Type 2 bridge over road and habitat -15 m Type 3 bridge -1.2 m x 1.2 m culvert	17 m culvert	concrete box culvert and diversion walls	After three years of monitoring spring amphibian migrations, it appears the diversion wall is successfully diverting the few vernal pool breeding amphibians that encounter it, but there is no evidence the crossing structure has been used. Substitute habitat also created
McGregor et al. 2015	Australia	Ornate burrowing frog Copper-backed brood frog Striped marsh frog Northern banjo frog	NA	Overpass: Hourglass shape. End widths20m Mid-width 10 m - 2 x Box culv underpasses 2.4 m high, 2.5 m wide - 3 x ca.3m stormwater culverts	Overpass 70 m Box culvert 48 m Stormwater Culverts circa 48 ? m	Habitat	Most species present on either side of Type 1 overpass are also located on the overpass itself.

Niemi et a. 2014	Finland	common frog moor frogs	Type 3 crossings over stream/river	1.5 m - 16.0 m wide by 1.5-8.0 m high	2-lane road bridges. Est up to 30 m	Dry path between bank and stream.	Paired comparison with controls between unfenced stream bridges with & without dry paths. Significantly fewer road kills at bridges with dry paths than bridges without dry path. Dry river-bridge paths reduce frog road mortality.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Rosell et al. 1997	Spain	Not stated	NA	39 circular (1-3 m diameter) and 17 rectangular cross section (4-12 m diameter) drains and other underpasses	Varied	Varied	Amphibians used 23% of circular and 59% of rectangular tunnels. Use was greater for wider tunnels with water at the entrances and within structures. Tunnels with steps or wells at the entrances or within large embankments were used less frequently
Van der Grift et al. 2010	Netherlands	Common frog Green frog-complex - species not determined - Marsh frog - Edible frog	NA	50 m	65 m with access ramps 110m (west) and 85m (east) on shallow gradient	Covered by a layer of 0.5 m topsoil.	Extensive use of overpass was determined over a 3 year study period.

Woltz et al. 2008	USA	Green frog Leopard frog	NA	diameters 300mm, 500m m, 600 mm, and 800 mm, lined with site soils.	4 x 3.0 m, one 6.1 m, and one 9.1m in length.	corrugated black PVC (polyvinyl chloride) pipes,	Crossing structures that function at least to some extent can be constructed out of round PVC pipe, that these structures should be at least 0.5m in diameter, that they should be lined with soil or gravel.

2. FROGS PASSAGE ENVIRONMENT

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Bellis et al. 2013	NA	NA	NA	NA	NA	NA	
Brehm 1989	Bare	Slotted surface	NA	NA	Swallowtail design initiated	NA	Channelling individuals to passage entrance considered very important
Cunnington et al. 2014	NA	NA	NA	NA	NA	NA	
Dodd et al. 2004	NA	NA	NA	NA	NA	NA	
Fitzsimmons and Breisch 2015	Culvert filled with soil and sand to leave 20-30% only of the total void area unfilled.	NA	NA	NA	Not used	Some rock and boards placed	No assessment
Gunson 2015	NA	NA	NA	part waterlogged	NA	A beaver screen was placed across the culvert ends.	
Hammer et al. 2014	Polymer concrete - bare	Slotted surface passage	Monitored	NA	NA	NA	Passage usage was not likely related to air temperature, humidity or light levels inside the tunnel,
Koehler and Gilmore 2014	Culverts,	NA	NA	Some flooded and temporarily dry	NA	NA	Passage use appeared to be relatively frequent and aquatic conditions may have assisted.

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Krikowski 1989	NA	NA	NA	NA	600 mm deep pitfall entrance One-way system with two passages	NA	In a compulsory one-way system the entrance area must be covered to make the area dark, so amphibians may better explore and move along passage.
Lesbarreres et al. 2004	Soil vs bare concrete	Unclear time of day of experiment	NA	NA	NA	NA	Water frog showed a preference for the passage as opposed open land, whereas Agile frog avoided passages. Both species showed a significant preference for the passage lined with soil.
Malt 2012	NA	NA	NA	NA	NA	NA	
Merrow 2007	Some soil in passage	NA	NA	Design to encourage some run-off - unclear	Wing walls only	NA	
McGregor et al. 2015	Open vegetated	NA	NA	NA	NA	NA	Natural vegetation appears to enable occupancy by most species present.
Niemi et a. 2014	NA	NA	NA	NA	NA	NA	
Rosell et al. 1997	NA	NA	NA	NA	NA	NA	

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Van der Grift et al. 2010	Naturalistic	NA	NA	Controlled variable	NA	Range of covers and shelters	Natural habitat establishes rapidly. Maintaining a humid environment on a Type 1 overpass and its ramps improves overpass use by frogs.
Woltz et al. 2008	sections lined with concrete, soil, gravel, or bare PVC.	four sections 600 mm diameter; 3.0-m-long pipe with overhead punctures of 0%, 0.65%, 1.3%, or 4.0% of the pipe's c/s surface area,	NA	NA	NA	NA	Green frogs showed significantly non-random avoidance of concrete lining and bare PVC.

3.FROGS BARRIERS

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Bellis et al. 2013	2.5 m	NA	NA	Chainlink	Barrier did not stop anurans crossing. 31% road mortality was anuran
Brehm 1989	400 mm	NA	70 mm	Molded plastic, curved with overhang	Purpose-built barrier is very effective for frogs but requires regular maintenance to prevent overgrown by grass
Cunnington et al. 2014	900 mm	NA	Buried to some extent	0.9-m-high plastic silt fencing	900 mm barriers keep frogs off roads.
Dodd et al. 2004	1.1 m wall has152 mm overhang Also: Standard fence with 2 guard rails (one on top of the other)	NA	NA prob 1.0 m + Standard has hardware cloth barrier below ground	Concrete	Mortality almost completely removed by placement of 1.1 m barrier other than for hylid treefrogs. Standard fence does not work well and requires a 20cm underground metal component to reduce mvt underneath.
Fitzsimmons and Breisch 2015	450mm	NA	150mm	Wood board and plastic	No detailed survey. The barrier was not high enough to stop a percentage of frogs crossing.
Gunson 2015	Est 1.2 m	Est 700mm	NA	Plastic cloth/sheeting	A maintained fence of this size should prevent frogs crossing
Hammer et al. 2014	NA	NA	NA	NA	

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Koehler and Gilmore 2014	**800 mm**			12 X 12 mm galvanized mesh funnel fences	Barrier appears to have functioned well
Krikowski 1989	NA	NA	NA	NA	
Lesbarreres et al. 2004	NA	NA	NA	NA	
Malt 2012	450 mm		70mm	Aquaculture (oyster farm) netting secured to rebar posts. Black polyethylene netting, 24" in width, with a ¼" mesh size fixed with UV-stabilized black zip ties. Rebar is 15mm.Top 6" of rebar posts are bent at 60° away from the highway	Did not work – many gaps and damaged by snow. Also the fence design was too low. 51% of individuals were observed climbing or jumping over fences.
Merrow 2007	Uncertain if wider scheme barrier has been built	300 mm rough faced wing walls only	NA	Blocs	
McGregor et al. 2015	NA	NA	NA	NA	Indications that the barriers are effective for frogs.
Niemi et a. 2014	No barrier	NA	NA	NA	
Rosell et al. 1997	NA	NA	NA	NA	
Van der Grift et al. 2010	Along the edges of the overpass 2.5m high embankments	NA	NA	Earth bund	Bunds appear to prevent access to the road
Woltz et al. 2008	four heights of barriers 300 mm, 600 mm and 900 mm	300	NA	corrugated plastic fences on wood posts	A 600-900mm high guide fence is required for the frog species tested.

6. TOADS

1. TOADS PASSAGE CONSTRUCTION & USE

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Bellis et al. 2013	USA	Not stated	NA	1.65m	124 m	NA	Barrier did not channel amphibians to passage
Brehm 1989	Germany	Spadefoot toad Common toad	Four study sites. One with tunnel study	200-1000mm	10-18 m	Corrugated iron Concrete Polymer concrete	Species use of passage varied from around 23% to higher levels (but small sample size). Main issue is individuals not locating passage entrance.
Cunnington et al. 2014	Canada	Eastern American toad	Varied	rectangular culverts of 100–200 cm	Ca 15 m est.	concrete	Presence of road drainage culverts does not reduce road mortality but fencing does.
Dodd et al. 2004	USA	Eastern narrow-mouthed toad Eastern spadefoot toad Southern toad	200-500m	Box: Two of 2.4 x 2.4 m Two of 1.8x1.8 m Round: Four of 0.9 m	44 m	Concrete	Mortality reduced and use of passages generally increased after fitting barriers.
Krikowski 1989	Germany	Common toad	Under 100 m	Three 400 mm One 600 mm	13-19 m 26 m	Concrete pipes	Large numbers of migrating toads may be moved under a road using 400-600 mm passages using the 'compulsory' one-way passage system.
Dulisse and Boulanger 2013	Canada	Western toad	NA	NA	10- 15 m est.	One plastic one metal.	Use of both passages was very low in relation to overall numbers of migrating individuals.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Langton 1989	UK	Common toad	C 200 m	200 x 200 mm	c. 16 m	Polymer concrete slotted surface passage	Use of a trip counter implies high use levels of a small surface passage for an outward adult long distance migration, with periods (days) of non-use.
Lesbarreres et al. 2004	France	Common toad	NA	500 mm	2.0 m	Concrete	
McGregor et al. 2015	Australia	Cane toad	NA	Overpass Hourglass shape. End widths20m Mid-width 10 m Two box culvert underpasses 2.4 m high, 2.5 m wide 3 x ca.3m stormwater culverts	Overpass 70 m Box culvert 48 m Stormwater Culverts circa 48 ? m	Habitat	Introduced non-native cane toads (R. marina) were the most regularly captured anuran on the overpass.
Patrick et al. 2010	USA	American toad	Not stated	Not stated	2-lane road Est 15 m	Not stated	Toads avoided crossing where there was a wetland within 15 m of the downslope of the road & did not show a strong preference for crossing near existing culverts.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Rosell et al. 1997	Spain	Not stated	NA	39 circular (1-3 m diameter) and 17 rectangular cross section (4-12 m diameter) drains and other underpasses	Varied	Varied	Amphibians used 23% of circular and 59% of rectangular tunnels. Use was greater for wider tunnels with water at the entrances and within structures. Tunnels with steps or wells at the entrances or within large embankments were used less frequently
Smith et al. 2009	Canada	Western toad	80 m to 110 m	Four 500mm	12.0 m	Slotted surface passage Polymer concrete	
Van der Grift et al. 2010	Netherlands	Common toad	NA	50 m	65 m with access ramps 110m (west) and 85m (east) on shallow gradient	Covered by a layer of 0.5 m topsoil.	Maintaining a humid environment on a Type 1 overpass and its ramps improves overpass use by toads.

1. TOADS PASSAGE ENVIRONMENT

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Bellis et al. 2013	NA	NA	NA	NA	NA	NA	
Brehm 1989	Bare	Slotted surface	NA	NA	Swallowtail design initiated	NA	Channelling individuals to passage entrance considered very important
Cunnington et al. 2014	NA	NA	NA	NA	NA	NA	
Dodd et al. 2004	NA	NA	NA	NA	NA	NA	
Krikowski 1989	NA	NA	NA	NA	600 mm deep pitfall entrance One-way system with two passages	NA	In a compulsory one-way system the entrance area must be covered to make the area dark, so toads may better explore and move along passage.
Dulisse and Boulanger 2013	NA	NA	NA	NA	NA	NA	
Langton 1989	NA	Slotted passage	Monitored variable	NA	NA	NA	Toads may 'hesitate' entering a passage if its temperature is lower than of the ground

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Lesbarreres et al. 2004	Soil vs bare concrete	Unclear time of day of experiment. Test sections very short in length removing light variation?	NA	Bare concrete an absorbant surface.	NA	NA	Toads showed a preference for the passage as opposed open land, and a significant preference for the passage lined with soil.
McGregor et al. 2015	Open vegetated	NA	NA	NA	NA	NA	Natural vegetation appears to enable regular occupancy passage
Patrick et al. 2010	NA	NA	NA	NA	NA	NA	
Rosell et al. 1997	NA	NA	NA	NA	NA	NA	
Smith et al. 2009	NA	NA	NA	NA	NA	NA	
Van der Grift et al. 2010	Naturalistic	NA	NA	Controlled variable	NA	Range of covers and shelters	Natural habitat establishes rapidly. Maintaining a humid environment on a Type 1 overpass and its ramps improves overpass use by toads.

2. TOADS BARRIERS

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Bellis et al. 2013	2.5 m	NA	NA	Chainlink	Barrier did not stop anurans crossing
Brehm 1989	450 mm	NA	70 mm	Molded plastic, curved with overhang	Purpose-built barrier is effective for toads but requires regular maintenance to prevent overgrowth by grass & herbs
Cunnington et al. 2014	900 mm	NA	Buried to some extent	0.9-m-high plastic silt fencing	900 mm barriers keep toads off roads.
Dodd et al. 2004	1.1 m wall has152 mm overhang Also: Standard fence with 2 guard rails (one on top of the other)	NA	NA prob 1.0 m + Standard has hardware cloth barrier below ground	Concrete	Mortality almost completely removed by placement of 1.1 m barrier. Standard fence does not work well and requires a 20cm underground metal component to reduce movement underneath.
Dulisse and Boulanger 2013	450mm	NA	150mm	Curved recycled plastic panel (one side only)	The barrier funnelled toads towards the passage entrances
Krikowski 1989	NA	NA	NA	NA	
Langton 1989	450 mm	NA	150mm	Curved recycled plastic panel (one side only)	The barrier funnelled toads towards the passage entrances and reduced road mortality.
Lesbarreres et al. 2004	NA	NA	NA	NA	
McGregor et al. 2015	NA	NA	NA	NA	Indications that the barriers are effective for toads.
Patrick et al. 2010	NA	NA	NA	NA	
Rosell et al. 1997	NA	NA	NA	NA	?

Smith et al. 2009	Ca 300 mm	NA	Buried	Plastic silt fencing and some buried half sections of HDPE plastic pipe.	Installation of 500 m drift fences effectively reduced road mortality for small number of toads.
Van der Grift et al. 2010	Along the edges of the overpass 2.5m high embankments	NA	NA	Earth bund	Bunds appear to prevent access to the road

7. SALAMANDERS

1. SALAMANDERS PASSAGE CONSTRUCTION & USE

SOURCE	**COUNTRY**	**Species**	**Dist between passages**	**Passage diameter**	**Underpass-Length**	**Passage material**	**Conclusions**
Allaback & Laabs 2002	USA	Santa Cruz long-toed salamander	The 2 of the six studied were circa 200 m apart.	6 passages 470 mm wide 320 mm high	11-12 m	AT 500 Surface passage slotted surface. screened with wire mesh (5 cm by 10 cm) to reduce predator access.	9% (4 of 44 adults; 3 captured the same night, 1 captured 2 days after being tagged) that encountered the drift fence passed through the passages.
Bain 2014	USA	California tiger Salamander	35 m	250 mm	22.0 m	3 passages solid steel with PVC pipe connector	Two of three crossing from observation or experiments were turn-backs. Passage operates for some individuals especially in wetter weather.
Brehm 1989	Germany	Great crested newt Smooth newt	Four study sites. One with tunnel study	200-1000mm	10-18 m	Corrugated iron. Concrete. Polymer concrete.	45% of migrating great crested and 12% of smooth newts passed through passages

Dodd et al. 2004	USA	Two-toed Amphiuma Greater Siren	200-500m	Box Two of 2.4 x 2.4 m Two of 1.8x1.8 m Round Four of 0.9 m	44 m	Concrete	Present in habitat and using passages but not recorded DOR.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Fitzsimmons and Breisch 2015	USA	Northern red salamander	46 m	Box culvert 1.5x 1.5 m	11 m	concrete	Passage used to some extent by salamanders.
Honeycutt et al. 2016	USA	Idaho giant salamander	NA	NA	20 m	NA	Where sedimentation occurs from roads and culverts, survival of salamanders could be reduced. Though culverts clearly do not completely block downstream movements, the degree to which culvert improvements affect salamander movements under roads in comparison to unimproved culverts remains unclear.
Jackson and Tyning 1989	USA	Spotted salamander	Under 100 m	200 x 200 mm	Circa 10 m	Polymer concrete surface passage	76% of salamanders entering passage continued through; one in four turned around.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Malt 2012	USA	Long-toed salamanders Rough-skinned newts	NA	8 culverts: 1 m PVC 2 m Conc 3 m CSP	Varies: 21.0 -37.0 metres.	Corrugated steel pipe. Plastic PVC Concrete	Only 4% of salamanders were observed passing through culverts with many escaping due to barrier permeability problems.
Matos et al. 2017	UK	Great crested newt Smoot newt	Circa 40 m	Two types Surface slotted Type 4 arch bridges 5.5 m wide 2.0 m high	Surface 30 m Arch 40 m	Slotted surface passage polymer concrete	Lower passage use by male newts, female and juvs. Movements skewed to autumn window. System has potential to partially mitigate species connectivity loss and fragmentation at the landscape scale.
Merrow 2007	USA	Spotted salamander	NA	-176 m Type 2 bridge over road and habitat -15 m Type 3 bridge -1.2 m x 1.2 m culvert	17 m culvert	concrete box culvert and diversion walls	After three years of monitoring spring amphibian migrations, it appears the diversion wall is successfully diverting the few vernal pool breeding amphibians that encounter it, but there is no evidence the crossing structure has been used. Substitute habitat also created
Patrick et al. 2010	USA	Spotted salamander	4 arrays 30-100 m apart each with 2 x 9.0 m wing fences	Varied 300 mm 600 mm 900 mm	Varied 3.0 m 6.0 m 9.0 m	PVC pipe	Spotted Salamanders showed little preference for culverts of different design

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Pagnucco et al. 2012 See also Smith below	Canada	Long-toed salamander	80-110 m	600 wide x 520 high	Circa 12 m	Polymer concrete slotted surface tunnel	Mortality decreased from 10% of the population to 2% following installation.. In 2009, 104 salamanders were documented using tunnels. Salamanders were 20 times more likely to use tunnels when traveling to the breeding site than when leaving. Long-toed Salamanders travelled an average of 27 m, and up to 78 m, along fences before successfully using tunnels. Models suggested that individuals found closer to tunnel entrances were more likely to use tunnels. A barrier & passage use estimate of 23% was determined for movements to the breeding site.
Rosell et al. 1997	Spain	Not stated	NA	39 circular (1-3 m diameter) and 17 rectangular cross section (4-12 m diameter) drains and other underpasses	Varied	Varied	Amphibians used 23% of circular and 59% of rectangular tunnels. Use was greater for wider tunnels with water at the entrances and within structures. Tunnels with steps or wells at the entrances or within large embankments were used less frequently.

SOURCE	COUNTRY	Species	Dist between passages	Passage diameter	Underpass-Length	Passage material	Conclusions
Smith et al. 2009	Canada	Long-toed salamander Tiger salamander	80 m to 110 m	Four 500mm	12.0 m	Slotted surface passage Polymer concrete	Of 278 adult long-toed salamanders associated with barriers 194 were adult LTS migrating to the Lake and 84 leaving the lake. Of LTD captured at the mouths of the 4 passages after passing through, 84 were moving towards the lake and 23 were leaving the lake.
Van der Grift et al. 2010	Netherlands	Great crested newt Smooth newt	NA	50 m	65 m with access ramps 110m (west) and 85m (east) on shallow gradient	Covered by a layer of 0.5 m topsoil.	Maintaining a humid environment on a Type 1 overpass and its ramps may improve overpass use by newts.

2. SALAMANDERS PASSAGE ENVIRONMENT

SOURCE	Substrate	Light	Temp	Wetness	Entrance deflectors	Passage Furniture	Conclusions
Allaback and Laabs 2002	NA	NA	NA	NA	NA	NA	Many individuals observed moving away from the tunnel entrances. Several individuals found near entrances did not use passages -none found greater than 16 m from entrances passed.
Bain 2014	Bare	NA	Measured but not in passage.	Of the 27 salamanders it took an average of 16 minutes to cross through a wet passage vs 24 minutes through a dry tunnel; significantly faster.	NA	NA	56% of salamanders rejected the passages. Other potential variables include airflow, internal temperature, vehicular sound, ambient light, substrate, or handling effects.
Brehm 1989	Bare	Slotted surface	NA	NA	Swallowtail design initiated	NA	Channelling individuals to passage entrance considered very important
Dodd et al. 2004	NA	NA	NA	NA	NA	NA	
Fitzsimmons and Breisch 2015	Culvert filled with soil and sand to leave 20-30% only	NA	NA	NA	Not used	Some rock and boards placed	No assessment

	of the total void area unfilled.						

SOURCE	**Substrate**	**Light**	**Temp**	**Wetness**	**Entrance deflectors**	**Passage Furniture**	**Conclusions**
Honeycutt et al. 2016	NA	NA	NA	NA	NA	NA	
Jackson and Tyning 1989	NA	Torchlight seemed to induce travel down passage	NA	Very important to salamander movement.	Sondiered important to reduce walkpast	NA	Background light levels at night may play an important role in passage use rate.
Malt 2012	NA	NA	NA	NA	NA	NA	
Matos et al. 2017	Natural soil in arch bridges	NA	NA	NA	Large concrete	NA	
Merrow 2007	Some soil in passage	NA	NA	Design to encourage some run-off - unclear	Wing walls only	NA	
Patrick et al. 2010	NA	NA	NA	NA	NA	NA	
Pagnucco et al. 2012	Bare- see also wetness.	NA	NA	Detailed rainfall measurements.	NA	NA	Salamander movement was positively correlated with rainfall particularly when salamanders were leaving the lake. Variation in passage use between passages was positively correlated with soil moisture of surrounding habitat.
Rosell et al. 1997	NA	NA	NA	NA	NA	NA	
Smith et al. 2009	NA	NA	NA	NA	NA	NA	

Van der Grift et al. 2010	Naturalistic	NA	NA	Controlled variable	NA	Range of covers and shelters	Natural habitat establishes rapidly. Maintaining a humid environment on a Type 1 overpass and its ramps improves overpass use by newts.

3. SALAMANDERS BARRIERS

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Allaback and Laabs 2002	760 mm	450 (curved)	150 mm	Curved plastic panels And silt fencing on posts	Amount & orientation of drift fence is a critical factor in system success.
Bain 2014	Under 500 mm	NA	Buried	low mesh or curved plastic fencing	Barriers at steep angles – 45 degrees - were effective but only covered a small proportion (20%?) of the migration width.
Brehm 1989	450 mm	NA	70 mm	Molded plastic, curved with overhang	Purpose-built barrier is very effective for newts but requires regular maintenance to prevent overgrown by grass
Dodd et al. 2004	1.1 m wall has152 mm overhang Also: Standard fence with 2 guard rails (one on top of the other)	NA	NA prob 1.0 m + Standard has hardware cloth barrier below ground	Concrete	Unclear if barrier had influence on Siren or snake-like salamander mortality as they rarely move above ground.
Fitzsimmons and Breisch 2015	450mm	NA	150mm	Wood board and plastic	No detailed survey but considered effective barrier. Without cutting and mowing vegetation will form bridge over barrier.
Honeycutt et al. 2016	NA	NA	NA	NA	

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Jackson and Tyning 1989	Under 400 mm	NA	buried	6 mm mesh on upland side, 3mm mesh (to stop young-of-the-year salamanders) on pond side.	Barrier efficiency given as around or above 68%
Malt 2012	450 mm	NA	70mm	Aquaculture (oyster farm) netting secured to rebar posts. Black polyethylene netting, 24" in width, with a ¼" mesh size fixed with UV-stabilized black zip ties. Rebar is 15mm.Top 6" of rebar posts are bent at 60° away from the highway	Did not work – many gaps and damaged by snow. Also the fence design was too low. 51% of individuals were observed climbing over fences.
Matos et al. 2017	Crica 500 mm with overhang 300 m in length, up to 50 m away from the road in w formation	NA	Circa 200mm	3mm plastic sheeting	Barriers guided newts to passage entrances.
Merrow 2007	Uncertain if wider scheme barrier has been built	300 mm rough faced wing walls only	NA	Blocs	

Source	Barrier Height (maximum)	Barrier Height (minimum)	Barrier buried (depth)	Barrier materials	Conclusions
Patrick et al. 2010	NA	NA	NA	NA	
Pagnucco et al. 2012 See Smith et al.	NA	NA	NA	W pattern drift fences leading to each tunnel were (distances combined ?) : 133 m (Tunnel 1) 159 m (Tunnel 2) 222 m (Tunnel 3) 274 m (Tunnel 4).	Long-toed Salamanders travelled an average of 27 m, and up to 78 m, along fences before successfully using tunnels. Models suggested that individuals found closer to tunnel entrances were more likely to use tunnels.
Rosell et al. 1997	NA	NA	NA	NA	**?**
Smith et al. 2009	Circa 300 mm (est)	NA	Buried	Silt fencing HDPE pipe half-cut with steel rebar posts.	Some sections of silt fencing was replaced with UV-resistant HDPE (high density polyethylene) black corrugated piping, with the goal of creating a more permanent, lower-maintenance fence.
Van der Grift et al. 2010	Along the edges of the overpass 2.5m high embankments	NA	NA	Earth bund	Bunds appear to prevent access to the road

APPENDIX D

Thoughts, questions and potential research areas for further consideration

1. What might unlimited barrier and passage investigations look like?

A large-scale investigation into road impact mitigation would be a substantial undertaking, even for one habitat. A linear strip of say 10 km in length, of even quality habitat and preferably with a hinterland extending to tens of Km in any direction would be studied for key indicator species. It would then be divided by solid barriers the width of the road, at variable distances and road noise, light and chemical impacts mimicked. Passages across the artificial road of different sizes would be introduced along it at different intervals and the impacts monitored with a similar control (non-intervention area) identified to a suitable distance away.

Such a single site experiment might take 5-10 years, cost $ Millions and ideally multiple replicates would give strength to analysis. This would need doing for every habitat and so is barely viable, but it would enable the comparative response of the different types of crossings to be scientifically compared in the normal way.

More realistic, would be comparing land already divided by roads with equivalent undisturbed land (effectively defining the road effect zone) and then introducing barriers (potentially also passages) and monitoring reaction, or population/community 'recovery' response. This would be less expensive and easier than the first scheme and begin with 2-3 years of basic populations monitoring of existing road sites. In this instance 10 paired study and control sites could perhaps be achieved for the price of one single large-scale remote habitat experiments.

At the finer scale, more species/species group based research would help to answer the questions with regards to what individual species need, and this may be very important for the rarest taxa, confined to a few remaining places. However recently disturbed populations may already be in severe flux and study may be influenced by unknown site history.

Detailed observations of single-species locations will be important, but can be expensive and limited in terms of 'what can be done' at individual locations. There are issues such as road-related built infrastructure and private property close by (access issues) and real estate value to road hinterlands of uncertain realisation. In these cases the practical value of findings may be 'too late' for those locations in terms of full reparation and long term retention of the species concerned. This however should not deter such studies as documenting site population reductions and extinctions is in itself valuable.

2. What might be the idealised research if funding was available ?

Ref.	Research Area	Description	Further comments
1	Identification of sensitive herp conflict areas past, current and future.	This can develop from comparing the CEHC map network, along with small landscape blocks for all high and very high risk or other herp species, overlain with information relating to road size and vehicle volumes.	May benefit from field verification of road/habitat locations for study for the range of species, habitat qualities and road types. Will provide a <u>checklist resource of research locations</u> for further/future research. Might make a good one-year desk and field study, examining multiple sites and recording locations details. May be possible to document the entire network. Could be achieved for key herp communities and all herp species in the long run.
2	Determination of possible current extent of use of non-engineered passages in the existing network.	As above, once identified, cameras could be used to determine a preliminary 'use or not' of a sample of existing non-engineered passage types (Types 1-5) to demonstrate extent of use. This seems to be the most time/cost-effective & perhaps only way to get a broad-based outlook with data, on which species might be using existing structures.	This is a vital component of understanding which of the ASHTTO approved Type 1-5 structures herpetofauna are already using. Try to record use by sensitive species of say 3 of each of the 5 crossing types (15 sites min and small water culverts (say 5 culverts) with range of roads of different sizes that include at least one sensitive species. Look at least one of each species groups (8 types) per 5 crossing Types where available (30-40 species/locations). May need additional resources.
3	Evaluation of ongoing herp connectivity projects	A number of existing projects have been visited and are being assessed for involvement, such as the 6-tunnel Highway 246 California tiger salamander crossings and long desert tortoise passage at SR58 new Hinkley Highway re-alignment.	Checklist supplied by Amy Golden (6.16) and other locations identified from the Malibu conference and Desert Tortoise consultations.
4	Improvements/enhancements to existing In-Situ California herp connectivity systems.	A range of concerns have been documented regarding existing systems and needs for improvements could be determined and implemented with better monitoring of them.	May be possible to partner existing bodies and gain stakeholder funding support for determining and implementing improvements and monitoring of them.
5	In-situ manipulations to examine mortality reduction using experimental barriers	Add temporary barriers (as cheap as possible) to existing non- engineered riparian crossings with high herp mortality rates, to try to assess value of low-cost (but permanent) retro-fitted barrier interventions.	Seasonal. Might attract partner support and participation.
6	Ex-situ experimentation with 'difficult' species	The design of 'most value' tests for a range of species from each group could be drawn up for both passages and barriers.	Such proposals could be made available to researchers and if resources allow one or two projects could be undertaken but may require additional resources.

2. **Less ambitious/costly research areas**

These areas might to some extent be affordable within the context of available or new smaller scale funding.

Highway Crossings

- Are herpetofauna using existing highway structures for movement across roads? If so, what is the relative permeability of most commonly built structures to different herpetofauna groups (Type 2-5)? How is degree of severance and use of non-engineered passages related to length or road size (lanes/traffic)?

- How much would populations benefit from addition of barrier fencing to existing structures?

- What are the most effective ways to simulate natural and artificial light, temperature and moisture within underpasses?

Barriers and End Treatments

- How does fence material (mesh vs. solid) influence passage use and how does this vary between species?

- Fence ends: how effective are barrier turn-arounds? Are there better feasible options?

- Access Roads: What are the best designs to extend barriers along road access points?