A Literature Review of the Effects of Roads on Amphibians and Reptiles and the Measures Used to Minimize Those Effects

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Executive Summary

Based on a literature review of over 200 references, this document addresses the adverse ecological effects of roads and traffic on amphibians and reptiles and examines methods to mitigate these effects. In this review, we consider the characteristics of the roads themselves as independent variables that potentially affect amphibians and reptiles, both directly and indirectly. Direct effects are considered to involve injury or mortality due to physical contact from vehicles or occurring during road construction. Indirect effects include habitat loss, fragmentation, and alteration of ecosystem processes at both fine and broad scales (physical, chemical, and biological). These changes may influence the behavior, survival, growth, and reproductive success of individual animals, cumulatively resulting in population-level consequences. Similarly, the summed effects on different species may influence the overall species richness and diversity in an area.

Roads are significant features of most landscapes, covering about 1% of the United States and ecologically influencing an estimated 15-20% of the US land area. A variety of road characteristics needs to be considered to understand the potential effects on amphibians and reptiles and their populations, including activities involved in road construction, the type of road, the amount of traffic, the density of roads in the area of interest, the spatial distribution and environmental context of the roads, and the presence and type of road crossing structures. Additionally, the intensity of road effects is influenced by a suite of biological characteristics of amphibians and reptiles, such as complexity of habitat requirements, skin permeability, thermoregulation, vagility (i.e., tending to change location over time), speed of movement, variation in population sizes, and spatial population structure. Taxa that undergo dispersal and move more slowly are more likely to suffer from road mortality.

The extent of the direct and indirect effects of roads has been revealed in numerous studies, with the greatest amount of data available for anurans and snakes. Excessive rates of mortality (thousands) have been documented for several species. Research indicates that the combined ecological effects may extend outward from the road edge beyond 100 meters, delineating a “road-effect zone.” Altered roadside habitats have been shown to modify amphibian and reptile behavior and movement patterns. Increased mortality and barriers to movement may influence species demography and gene flow, consequently having an impact on overall population stability and persistence.

Although relatively few studies address the population-level consequences of roads, population declines in several anuran, snake, and tortoise species have been shown to be associated with roads. Species with restricted distributions and/or small population sizes appear to be more vulnerable to extinction because of their sensitivity to stochastic changes. Species reliant on metapopulation structure are considered more vulnerable to habitat fragmentation because subpopulations periodically go extinct locally and must be re-established by dispersal from neighboring sources.

Road-crossing structures and other methods (e.g., signs and road closures) have been used with varying degrees of success to address the negative impacts of roads on amphibians and reptiles. Types of road-crossing structures include amphibian and reptile tunnels, wildlife culverts, modified drainage culverts, wildlife underpasses, and wildlife overpasses. Several studies have shown that these passages can be very effective in decreasing levels of road mortality and isolation. The effectiveness of road-crossing structures is influenced by attributes such as structure type and dimensions, substrate and placement with respect to particular habitats.

We provide recommendations for future work to understand and mitigate the effects of roads on amphibians and reptiles, including: (1) conducting research to determine if roads and vehicles inhibit movement of amphibians and reptiles; (2) investigating the diversity of impacts that roads and traffic have on amphibian and reptile populations (cf. road mortality) at broad spatial and temporal scales (> one generation); (3) acquiring and incorporating information on the location and importance of road-kill sites to improve placement of road-crossing structures; (4) identifying key habitat features that serve as corridors to movements through GIS spatial modeling; (5) conducting field experiments and monitoring studies that evaluate the efficacy of road-crossing structures and determine maintenance requirements; (6) establishment of performance standards for structures based on characteristics and needs of wildlife; and (7) developing ways to communicate this information effectively and efficiently to all interested parties and provide means for feedback as an ongoing, iterative process.

Introduction

The goal of this document is to review the effects of roads on amphibians and reptiles with an emphasis on the adverse biological and ecological effects and how to mitigate them.

Recently, concerns regarding observation of widespread amphibian and reptile population declines have been published (Alford and Richards 1999; Gibbons et al. 2000; Stuart et al. 2004). A document synthesizing what is currently known about road impacts is needed to facilitate investigations into the role that roads may play in contributing to those declines. Unlike many factors (such as global warming, increased ultra-violet radiation, and disease), the prospect of mitigating the adverse effects of roads seems more attainable. We believe that the better we understand this subject, the more effective we will be in minimizing the detrimental effects that our roads have on these animals.

This document includes a bibliographic database of the effects of roads on amphibians and reptiles that may be searched by author, taxonomic group, geographic area, and subject (e.g., fragmentation, genetic effects, road-crossing structures) within the ISI ProCite and Adobe Acrobat programs.

Our literature review is more restricted than the database and specifically addresses the following questions: (1) What is the scientific evidence for the need to provide mitigation for the detrimental effects of roads on individual amphibians and reptiles and on their populations? and (2) What types of methods have been used to address detrimental impacts and, if known, how effective have they been? We consider how types of roads, the surrounding environment, and different species and life stages may influence the effectiveness of mitigation. This report does not attempt to provide detailed specifications concerning the construction of road-crossing structures, as these suggestions will vary with each project. Finally, the report contains recommendations for future actions (experimental studies, meetings, publications, workshops, etc.) to better address the issue of the detrimental effects of roads on amphibians and reptiles.

Methods

To create a bibliography of the literature addressing the ecological effects of roads and traffic on amphibians and reptiles including mitigation efforts, we conducted literature searches at the University of Wisconsin (Madison; Stevens Point), University of Georgia, Savannah River Ecology Laboratory, and Idaho State University libraries. Articles summarizing original investigations, reviews, and conference proceedings were located, some through interlibrary loan. The majority of publications were found by searching journals and databases including

Agricola, Biological Abstracts, BioOne, Ecology Abstracts, Science Citation Index, and Wildlife Worldwide. Keywords used to search the databases included: alligator, amphibian, bridge, construction, culvert, density, effects, fragmentation, frog, habitat, highway, intensity, lizard, mitigation, movement, mortality, overpass, population, reptile, road, road-kill, salamander, snake, toad, tortoise, traffic, tunnel, turtle, underpass, and viaduct.

In addition to the references in print, the survey revealed several literature databases that are in electronic form.

1. The Center for Transportation and the Environment (CTE) maintains several databases of environmental research including the Wildlife Ecology in Transportation bibliographic database of literature and web sites on wildlife issues in transportation. {www.itre.ncsu.edu/cte/wildlife.htm}
2. The U.S. Department of Transportation, National Transportation Library maintains the TRIS Online Database that contains 491,577 records of published transportation research (as of July, 2004). The International Transport Research Documentation database is also available for additional international material. {ntl.bts.gov/}
3. The U.S. Department of Transportation - Federal Highway Administration maintains a Critter Crossing website that serves as a database for current mitigation efforts to reduce wildlife mortality on roads. {www.fhwa.dot.gov/environment/wildlifecrossings/}
4. The Swedish National Road Administration Library Database contains 38,000 records of Swedish and foreign literature on the design, construction and maintenance of roads, bridges and tunnels, and on road traffic safety, the environment, transport and vehicle technology. {www.vv.se/biblio/english/}
5. Road-RIPorter Roads Bibliographic database was compiled by the Wildlands Center for Preventing Roads (CPR), and contains approximately 10,000 citations - including scientific literature on erosion, fragmentation, pollution, effects on wildlife, aquatic and hydrological effects, and other information on the impacts of roads. {www.wildlandscpr.org/databases/index.html}

The references cited in this paper are included in a literature database maintained by the authors in ProCite format. This database is organized alphabetically by author's last name as well as categorically by subject and taxa and currently includes about 250 references. This document and the accompanying ProCite database are also available in Adobe Acrobat (PDF) format.

Effects of Roads

Organization

To provide a framework for describing, relating, and summarizing the results from the diverse literature on the effects of roads on amphibians and reptiles, we developed the conceptual approach illustrated in Figure 1. The characteristics of the roads themselves (i.e., construction activities, road type, the overall road density in an area, and traffic level and patterns) are considered independent variables that potentially affect amphibians and reptiles, both directly and indirectly. Direct effects are considered to involve injury or mortality occurring during road construction (e.g., inadvertent burial or death from blasting) or subsequent physical contact with vehicles. Indirect effects include habitat loss, fragmentation, and alteration (e.g., changes in temperature, moisture, light, noise, pollutants, or quality of available habitat). Such changes may influence the behavior, survival, growth, and reproductive success of individual animals. For example, increases in the noise and light levels may disorient an animal, preventing them from crossing a road by posing a risk or obscuring cues necessary to follow certain paths, thus interfering with access to cover, food, and mates. The summed direct and indirect effects on individual animals may have population-level consequences (e.g., size, spatial structure, and persistence). Similarly, the summed effects on different species may influence the overall number of species in an area (i.e., species richness). These effects may be especially problematic when they affect sensitive, threatened, or endangered species or interfere with important ecosystem processes.

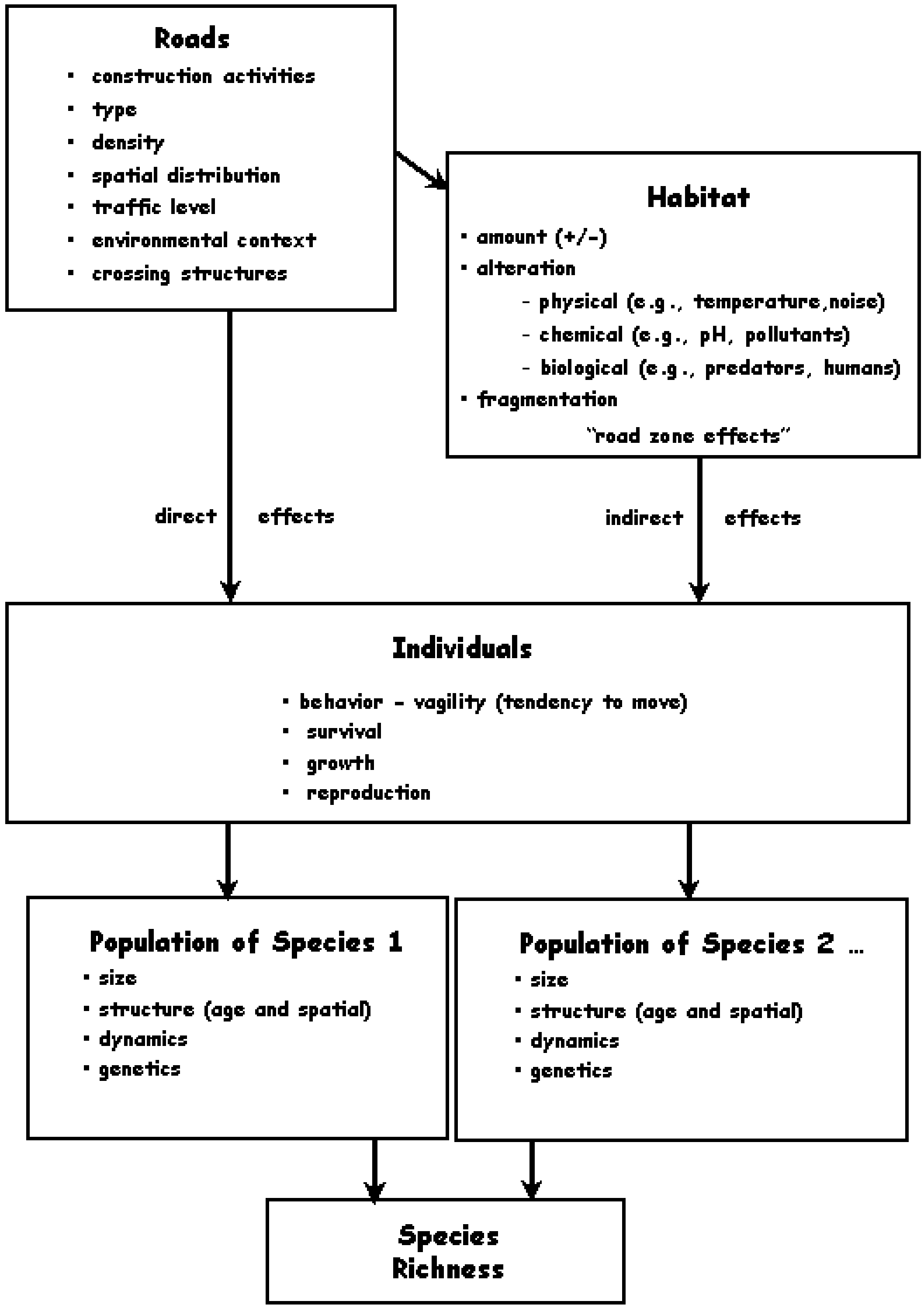

Figure 1. Conceptual framework for describing, relating, and summarizing results from the literature on the effects of roads on amphibians and reptiles.

Characteristics of Amphibians and Reptiles That Influence Susceptibility to Road Effects

Amphibians and reptiles possess a variety of biological characteristics that influence their vulnerability to road effects. Factors influencing the frequency, speed, distance, and timing of movements can increase susceptibility to direct road mortality. Characteristics such as ectothermy (body heat derived primarily from external sources), skin permeability (esp. amphibians), and behavioral responses to light and noise can increase susceptibility to indirect effects. In addition, individual longevity, and population variability and spatial structure may influence population size and persistence.

The habitat requirements of amphibians and reptiles vary seasonally; therefore the distribution of resources across the landscape relative to roads can influence mortality. These resources are associated with refuge, mates, and prey that tend to be concentrated in distinct habitats that are patchily distributed. For example, some snakes within northern temperate regions make a loop-like migration from a communal hibernaculum to summer foraging habitats across relatively long distances [up to 17.7 km for the red-sided garter snake (*Thamnophis sirtalis parietalis),* Gregory and Stewart 1975; up to 11 km for the western rattlesnake (*Crotalus viridis)*, Duvall 1986]. Additionally, amphibians migrate in mass numbers between breeding ponds and terrestrial habitats (Holdgate 1989; Ashley and Robinson 1996; Semlitsch 2000). These taxa are therefore dependent on "landscape complementation" (a measure of proximity of critical habitat types and dispersal ability of the organism) to successfully complete their life cycles (Dunning et al. 1992; Pope et al. 2000). When roads fragment such habitats, the probability that individuals will be killed or injured by traffic during movements in search of resources, increases, as does the resistance of the landscape to such movements (Fahrig and Grez 1996).

An individual's vulnerability to road mortality is influenced by dispersal ability as well as the spatial scale and frequency of movements. Research indicates that more vagile (i.e., tending to change location over time) species are more likely to suffer from road mortality. In studying five amphibian species across a gradient of habitat loss, Gibbs (1998b) determined that species with low dispersal rates were more likely to persist in landscapes with low habitat cover, such as roadside areas, than vagile species. Carr and Fahrig (2001) suggest that as dispersal distances increase so does the likelihood of road encounter, and consequently mortality risk for a given anuran species. Furthermore, the population density of the more vagile northern leopard frog was negatively impacted by traffic density within a 1.5 km radius of a pond; however, there was no evidence that traffic density impacted the population density of the less vagile green frog (*Rana clamitans*). Similarly, a study designed to examine the mortality patterns for snake populations in France provides evidence that species which move frequently over long-distances experience higher mortality than sedentary foragers (Bonnet et al. 1999). The researchers concluded that the movement patterns of snakes might be indicative of their susceptibility to direct mortality.

Studies associate peaks of road mortality with higher movement frequencies due to season, sex, and life stage. For amphibians, road mortality may be proportionally high during pulses of movement related to fluctuations in water level (Smith and Dodd 2003), breeding (McClure 1951; Hodson 1966; Fahrig et al. 1995; Ashley and Robinson 1996), and dispersal (McClure 1951; Palis 1994; Ashley and Robinson 1996; Smith and Dodd 2003). Reptile examples comprise migratory behavior including movements related to fluctuations in water level (Bernardino and Dalrymple 1992; Aresco 2003; Smith and Dodd 2003; D. Jochimsen unpub. data), adult males searching for mates (Bonnet et al. 1999; Whitaker and Shine 2000; D. Jochimsen unpub. data), nesting migrations of adult females in the spring (Fowle 1996; Bonnet et al. 1999; Haxton 2000; Baldwin et al. 2004), and neonatal dispersal during late summer or early autumn (Bonnet et al. 1999; Enge and Wood 2002; Smith and Dodd 2003; D. Jochimsen unpub. data).

Vulnerability to road mortality may also increase when movement pulses coincide with increased traffic volume. Dalrymple and Reichenbach (1984) noted a considerable rise in the road mortality of snakes, including the endangered plains garter snake (*Thamnophis radix)*, when fall migrations to over-wintering burrows overlapped with intensified levels of sportsmen activity in a wildlife area in Ohio. Data collected on the directionality of massasauga rattlesnakes (*Sistrurus catenatus*) caught crossing Loop Road in Squaw Creek Wildlife Refuge, Missouri verified seasonal variation of habitat use within this population (Seigel 1986). Snake movements occurred during periods of increased human visitation to the refuge, and resulted in higher road mortality during both spring and autumn migrations. Additionally, Bernardino and Dalrymple (1992) found that the seasonal migration of snakes in Everglades National Park was significantly affected by the fluctuation of water levels. An increased movement of snakes during the dry season coincided with a greater influx of visitors to the park, resulting in 56% of all annual road casualties. Conversely, several studies suggest that nocturnally active species have reduced susceptibility to road mortality due to lower traffic levels (Dodd et al. 1989; Enge and Wood 2002; D. Jochimsen unpub. data).

Crossing behavior, namely speed and angle, can also influence the ability of individuals to successfully cross the road. Slower-moving animals or those that cross at a wide angle take longer to cross the road, thereby experiencing a greater risk of mortality. Few studies have examined the speed of crossing animals, but slow movements of amphibians (Hels and Buchwald 2001), turtles (Gibbs and Shriver 2002), and snakes (Andrews 2004) have been documented. While the speed of amphibians and turtles is likely fairly consistent across species within each group, the crossing speeds of snakes vary significantly interspecifically, insinuating that snakes could suffer a greater range of road mortality rates than other taxa (Andrews 2004). Although intraspecific variation in speed has not yet been documented for road crossing, it is thought that the differences do exist as evidenced by the comparison of gravid and non-gravid female green snakes (*Opheodrys aestivus*) (Plummer 1997). Finally, essentially nothing is published regarding crossing angles for herpetofauna. We are not aware of papers that have presented field data for crossing angles for amphibians. The two reptile studies of which we are aware were performed with snakes, and both found individuals to consistently move perpendicularly across the road, taking the shortest route possible (Andrews 2004, Shine et al. 2004).

Several other behaviors and characteristics may also increase susceptibility to road-related mortality. For example, some species of snakes may be attracted to road surfaces to thermoregulate (Klauber 1939, Sullivan 1981; Ashley and Robinson 1996) or scavenge from carcasses (Florida cottonmouths (*Agkistrodon piscivorus conanti*) are an example (Smith and Dodd 2003)), and some species of toads may use roads under streetlights to forage for insects (Neill 1950; D. Jochimsen, pers. obs.). McClure (1951) noted that peak mortality of snakes (all species included) occurred during May and October when individuals were frequently observed basking on road surfaces during cooler temperatures. Habitat changes within the vicinity of the road surface may attract certain species thereby creating a population sink (discussed further in the Road Effects on Amphibian and Reptile Populations section of this document). Many amphibians and reptiles are relatively slow moving, and the greater amount of time required to cross the road surface increases the likelihood of mortality (Hels and Buchwald 2001). Also, migratory behaviors are largely genetically controlled, and therefore may limit an individual's ability to readily adapt to a road that interferes with its route (Langton 1989). Finally, many species of snakes present a relatively large target as they crawl across roadways, which may affect the frequency of intentional killing (Whitaker and Shine 2000) or collecting by humans (Dodd et al. 1989).

The indirect effects of roads on amphibians and reptiles via changes in micro-environmental conditions are influenced by such biological characteristics as ectothermy and skin permeability. Changes in thermal and moisture characteristics in the area altered by roads and traffic may prevent amphibians and reptiles from occupying roadside habitat or crossing roads. Amphibians are potentially limited by the microhabitat variables of canopy and litter cover (deMaynadier and Hunter 1998). In addition, amphibians are sensitive to the various toxic substances (emitted from vehicles or associated with road maintenance) that are soluble in fatty tissues and to heavy metals that may accumulate in their bodies. Exposure to these compounds could alter reproduction and have lethal effects in the long term (Lodé 2000). The microhabitat effects of roads on reptiles are not known.

The stability of amphibian and reptile populations in the vicinity of roads may be affected by a variety of factors. In addition to the variables mentioned previously, individual longevity, genetic variability, and spatial structure may influence population size and persistence. Studies provide evidence that road mortality may detrimentally impact populations of species with low reproductive rates (Rosen and Lowe 1994; Ruby et al. 1994; Fowle 1996; Kline and Swann 1998; Gibbs and Shriver 2002). Individuals that inhabit small home ranges and are limited in dispersal ability are subject to the isolation effects resulting from fragmentation (Andrews 1990; Boarman and Sazaki 1996). Species with a metapopulation structure (i.e., a group of individual subpopulations that depend on dispersal among one another for survival of the population as a whole) are considered vulnerable to habitat fragmentation because their subpopulations periodically go extinct locally and must be re-established through dispersal from neighboring sources (Lehtinen et al. 1999).

Characteristics of Roads

Roads are major features of most landscapes that impose an array of ecological effects. The magnitude of construction is significant with approximately 6.3 million km of public roads throughout the contiguous US as of 2001 (USDT 2002). With an average width of 3.65 m per lane, construction has destroyed at least 4,784,351 ha of land and water bodies (Trombulak and Frissell 2000). A recent study calculated that 73% of the total land area, including all cover types, is within 810 meters of a road (Riitters and Wickham 2003). Road corridors, the area including roads and their maintained borders, cover about 1% of the United States, an area equivalent in size to South Carolina with 10 percent of the road length in national forests, and one percent interstate highways (Forman 2000). Additionally, when considering effects that extend beyond the immediate road surface, roads with vehicles ecologically influence an estimated 15-22% of the nation's land area (Forman and Alexander 1998). A variety of road characteristics need to be considered to understand what the potential effects on amphibians and reptiles and their populations might be, including the activities involved in road construction, the type of road, traffic volume, the road density in the area of interest, the spatial and environmental context of the roads, and the presence and characteristics of road-crossing structures.

Road construction results in habitat loss and alteration and may incur direct mortality or physical injury to any sessile or slow-moving organism within the path of the developing road (Trombulak and Frissell 2000). Goodman and colleagues (1994) reported that a large number of radiated tortoises (*Geochelone radiata*) fell down a steep embankment adjacent to an unfinished road in Madagascar. They were unable to escape and consequently died from exposure to sun, heavy rainfall, and human collection. In Yellowstone National Park, western toad (*Bufo boreas*) tadpoles were trapped between a road under construction and an erosion barrier, which necessitated physically moving the tadpoles over the barrier to the wetland (C. Peterson, pers. obs.). The timing of road construction activities may have a large influence on their effects because of large seasonal differences in the movement patterns and habitat use of some amphibians and reptiles. For example, in eastern Idaho, late summer blasting of a rocky area in which terrestrial garter snakes (*Thamnophis elegans*) overwintered, probably resulted in higher mortality than if the blasting had taken place earlier in the summer when the snakes were dispersed (C. Peterson, pers. obs.). Furthermore, recently metamorphosed western toads were inadvertently buried during blading of the shoulder areas along the Grand Loop Highway north of Old Faithful in Yellowstone National Park (C. Peterson, unpub. data). Construction may also result in the loss of certain habitat features, such as exposed rocky areas, that previously supported snakes and their prey base (e.g. eastern kingsnakes (*Lampropeltis getula*), Smith and

Dodd 2003). Given that construction activities often have unforeseen consequences, it is advisable for a biologist to perform environmental assessments of the road sites before, during, and after construction.

Several road aspects of potential influence include age, access, construction materials and size. When interpreting road effects on the surrounding wildlife, it is important to consider the history of a particular road, including opening date, and any changes concerning vehicle access. Road types range from rural dirt and forest service roads to paved two-lane highways and interstate freeways; 3.65 million km of roads in the conterminous US are paved and 79% of all road types lie within rural areas (Forman et al. 2003). The subsequent maintenance of road surfaces and corridors (use of de-icing agents, mowing etc.) may impact amphibians and reptiles, and is addressed within the Indirect Effects of Roads via Habitat Changes section of this document. The respective widths and densities of roads, in addition to associated traffic levels and speeds, affect road-kill rates (Forman and Alexander 1998).

Studies suggest that low traffic volumes may be sufficient to cause high levels of amphibian mortality, but generally the mortality rate increases with traffic volume. A flow of 10 vehicles per hour resulted in 30% mortality of females in a population of common toads (*Bufo bufo)* migrating across a road to and from a breeding pond in the Netherlands (van Gelder 1973). Based on these data, the author estimated that a higher traffic load of 60 vehicles per hour would result in 90% mortality. Similar mortality rates were estimated in Germany where a flow between 24-40 vehicles per hour may kill at least 50% of the common toad migrants (Heine 1987; Kuhn 1987). A study conducted in two regions near Ottawa, Canada found a positive relationship between proportions of dead anurans on roads and higher traffic intensity; anuran density, as measured by chorus intensity, decreased (Fahrig et al. 1995). The averages of annual daily traffic for this study varied from 500-3,500 (low) to 8,500 –13,000 (high). Lodé (2000) found that amphibian mortality exponentially increased with traffic volume on a motorway in France. Several other studies concluded that mortality risk for amphibians was positively correlated with an increase in traffic intensity (Hels and Buchwald 2001; Joly et al. 2003). A recent study conducted in Kouchibouguac National Park, Canada, revealed differences in species response to the nightly variation of traffic intensity along a 20-km road segment (Mazerolle 2004). Road casualties of American toads (*Bufo americanus*) increased with vehicle density, ranid frog mortality was highest under moderate density, salamander mortality remained constant across all volumes, and the number of dead spring peepers (*Pseudacris crucifer*) decreased in relation to increased traffic. Interestingly, these patterns were detected despite a fine-scale variation of only 5-26 vehicles per hour.

The relationship between traffic volume and mortality of reptiles is, however, not as clear. The proportion of massasaugas, an endangered species of rattlesnake, found dead on the road varied seasonally; mortality rates were highest in the autumn (36.1% of captures) and correlated with peak traffic patterns (Siegel 1986). Another study documented a positive correlation between the number of vehicles recorded traveling through Everglades National Park and the number of snakes found dead or mortally injured on a monthly basis (Bernardino and Dalrymple 1992). Conversely, several studies have found that traffic volume was not significantly correlated with the number of road-killed reptiles and attribute this to traffic decimating populations adjacent to the road prior to the study period (Nicholson 1978; Dodd et al. 1989; Enge and Wood 2002), discrepancies in the timing of traffic and survey data collection (Smith and Dodd 2003), or variance in species composition and densities along road sections (Enge and Wood 2002).

Several studies infer that peak traffic levels create a barrier to movement across roads by inflicting high rates of mortality. Franz and Scudder (1977) documented the fate of 132 snakes attempting to cross U.S. 441 along Paynes Prairie. The majority of snakes were killed in the lane adjacent to the road shoulder where they entered the highway (55% of which were killed by the first passing vehicle). Only 21 snakes managed to reach the far lane of the two-lane highway, where they were ultimately run over. Smith and Dodd (2003) concluded that given the high traffic volume on roads crossing Paynes Prairie, virtually all crossing attempts by wildlife would result in death. Over the yearlong survey, only 26 animals were observed alive on the road surface. Eleven of these individuals were discovered basking within the right-of-way (examples include American alligators (*Alligator mississippiensis*) and cottonmouths), while 15 individuals were spotted during attempts to cross the highway. Only three animals crossed successfully (seven were injured or road-killed and five returned to the prairie), including a Florida box turtle (*Terrapene carolina bauri*) and a common snapping turtle (*Chelydra serpentina*), and did so during low traffic levels. Both of these studies observed few individuals within the grassy median that separates the north and south bound lanes of the highway, further supporting a low success rate of crossing. Aresco (2003) found that U.S. 27 creates an impenetrable barrier along the 1.2 km section bisecting Lake Jackson in Tallahassee, Florida. This highway experiences traffic volumes of 21,500 vehicles/day and almost 9,000 turtles have been found dead on the road. Using a model from Hels and Buchwald (2001), Aresco estimated the likelihood of mortality was 0.98. This estimate is potentially conservative, as there has been no evidence of turtles reaching the median (M. Aresco, pers. comm.). However, even if peak volumes are low, road casualties may be quite high. Two studies conducted along rural roads document reptile mortality to be 72% in the state of Louisiana (Fitch 1949) and 82% in Georgia (Herrington and Harrelson 1990). On rural roads in Florida, 93% of observed snakes were discovered dead despite the fact that traffic was less than 1,000 vehicles per day (Enge and Wood 2002).

Road density is a useful index for addressing the ecological impacts of roads and vehicles on landscape connectivity and wildlife movement and is readily measured as the total length of roads per unit area (Forman and Hersperger 1996). Increased road density inevitably results in an increased number of road-killed individuals and a reduction in the amount of available habitat, which could ultimately lead to reduced population sizes. Riiters and Wickham (2003) suggest that the relative contribution of roads to fragmentation of the landscape is greatest within heavily forested areas of the U.S. including the Pacific Northwest and Appalachian Mountains due to high road densities. Several studies have examined the effects of road density on amphibian populations and species richness (Dickman 1987; Halley et al. 1996; Vos and Stumpel 1996; Findlay and Houlahan 1997; Vos and Chardon 1998; Knutson et al. 1999; Lehtinen et al. 1999; Findlay and Bourdages 2000). These studies will be discussed in more detail in the Road Effects on Species Richness section of this document.

Road placement within the landscape can also influence road-kill locations, rates, and species presence. For example, the expanding literature indicates that road placement within the vicinity of wetlands and ponds may result in associated high rates of road mortality (Ashley and Robinson 1996; Fowle 1996; Forman and Alexander 1998; Smith and Dodd 2003). There are few studies that investigate how the pattern and spatial distribution of roads may influence the area affected in relation to use by amphibians and reptiles. Gibbs and Shriver (2002) developed a model that demonstrated that road distribution could have a negative impact on the population stability of turtles. Porej et al. (2004) modeled the association between presence of amphibian species within wetlands (based on survey data) and the surrounding landscape components. The probability of tiger salamander (*Ambystoma tigrinum*) occurrence was negatively associated with the density of paved roads within 1 km of a wetland site, as was overall salamander richness. Road configuration has been shown to visibly affect potential habitat loss in simulated elk (*Cervus elaphus*) habitats (Rowland et al. 2000). The authors concluded that evenly spaced roads had the most extensive impact on surrounding habitat and randomly spaced roads had the least. Clumped road patterns produced comparatively larger continuous blocks of unaffected habitat. Furthermore, this study demonstrated that it is possible to have an area with relatively high road density, but habitat loss equivalent to an area with lower road density, depending on the spatial distribution of roads. This distribution in turn affects habitat use and selection by wildlife. Boarman and Sazaki (1996) found that most of a desert tortoise's (*Gopherus agassizii*) activity occurs within the same general area, defined as their home range. If an individual's home range is bisected or in the immediate vicinity of a highway, the animals are more likely to use highway edge habitat or cross the road in search of resources or mating opportunities, thereby increasing the probability of mortality.

In addition, roads facilitate an increased use of surrounding habitats by humans, future development of an area, and the hunting and collection of amphibians and reptiles. A survey conducted along a 4.34 km stretch of highway in Virginia counted 427 discarded bottles that had trapped a total of 795 vertebrates, with a mean of 1.85 individuals per bottle (Benedict and Billeter 2004). Animals were captured presumably during exploration and unable to escape due to the smooth interior, narrow diameter of the opening, remaining liquid, and orientation of the bottles (openings facing uphill decreased likelihood of escape). Although the majority of captures were of northern short-tailed shrews (*Blarina brevicauda)*, surveyors recorded the casualties of 28 individual lizards and plethodontid salamanders. The authors concluded that roadsides with such refuse potentially pose a conservation threat to small vertebrates. Road construction often occurs concomitantly with urban development, further increasing habitat loss, fragmentation, and mortality of wildlife within the vicinity of activities. Finally, roads grant easy access to the movement corridors of amphibians and reptiles causing populations to suffer under the pressure of human predation and collection (Bennett 1991; Krivda 1993; Ballard 1994; Mc Dougal 2000).

The installation of road-crossing structures and other compensatory methods may increase road permeability for wildlife. The presence of such features or measures should be considered when estimating the effects that specific roads exert on local populations of amphibians and reptiles. We will address the implementation of these measures in a later section of this document.

Direct Effects: Road Mortality

The most evident effect of roads on wildlife is mortality inflicted by vehicles. “Sometime during the last three decades, roads with vehicles probably overtook hunting as the leading direct human cause of vertebrate mortality on land” (Forman and Alexander 1998). Numerous studies have investigated road-induced mortality of amphibians and reptiles based on road-transect surveys. This mortality primarily occurs as these animals move between habitat patches. Some studies document the amount of traffic mortality within these two groups but don’t distinguish among orders or species. Ehmann and Cogger (1985) estimated that 4.45 million anurans and 1.03 million reptiles get killed annually on roads throughout Australia. These are the largest approximations reported anywhere in the literature and are often cited within reviews concerning road effects. However, these estimates were derived from data collected from four surveys of four different segments of roads ranging from 2.5 to 25.1 km, and then extrapolated to account for the total length of roads passing through appropriate habitat. Fuellhass et al. (1989) discovered the carcasses of 298 amphibians (6 species) and 7 reptiles (1 species) during a one-year study on two road segments (totaling 8.5 km) located in Germany. Road surveys in Saguaro National Park documented the mortality of 427 amphibians and 374 reptiles over a three-year period (Kline and Swann 1998). A review of road surveys conducted in central Europe, reported that amphibians were observed more frequently than road-kills of four other vertebrate taxa, comprising 70.4 to 88.1 percent of all observations (Puky 2003).

Actual road-kill counts may be underestimated due to a variety of factors. Several studies report high incidences of carcass removal by scavengers (Kline and Swann 1998; Enge and Wood 2002; Smith and Dodd 2003). Results from all-night surveys conducted in Saguaro National Park indicated that, on average, no more than 24% of the animals killed between sunset and early morning persisted on the road long enough to be observed during regular surveys (conducted between 0830 and 1200 hours) (Kline and Swann 1998). Enge and Wood (2002) report similar data from the pedestrian survey of snake communities in Florida, where 70.5% of the 207 snake carcasses on the road were gone by the following day, and less than 1% remained for 5 or more days. Additional factors that may influence count data include movement of individuals after being struck and before dying (Dodd et al. 1989; D. Jochimsen, unpub. data), displacement of carcasses from the road by passing vehicles (Enge and Wood 2002; D. Jochimsen, unpub. data), obliteration of carcasses during high traffic volumes (Clevenger et al. 2001; Hels and Buchwald 2001; Smith and Dodd 2003), abiotic conditions influencing the persistence of specimens (K. Andrews, unpub. data), and observational error due to small body size and incomplete remains (Boarman and Sazaki 1996; Mazerolle 2004). Survey design may bias detection, as small animals that might not be observed from a vehicle might be counted when conducting the transect on foot (Enge and Wood 2002; Smith and Dodd 2003). Surveys may be timed to coincide with periods of wildlife activity to document levels of maximum road mortality. Finally, yearly variation of environmental factors may impact mortality estimates, so that surveys conducted in a particular year may not provide an accurate representation of overall trends (Ashley and Robinson 1996).

The following sections categorize studies of the effects of direct road mortality by amphibian and reptile order or suborder. These studies are quantified by taxa in Figure 2.

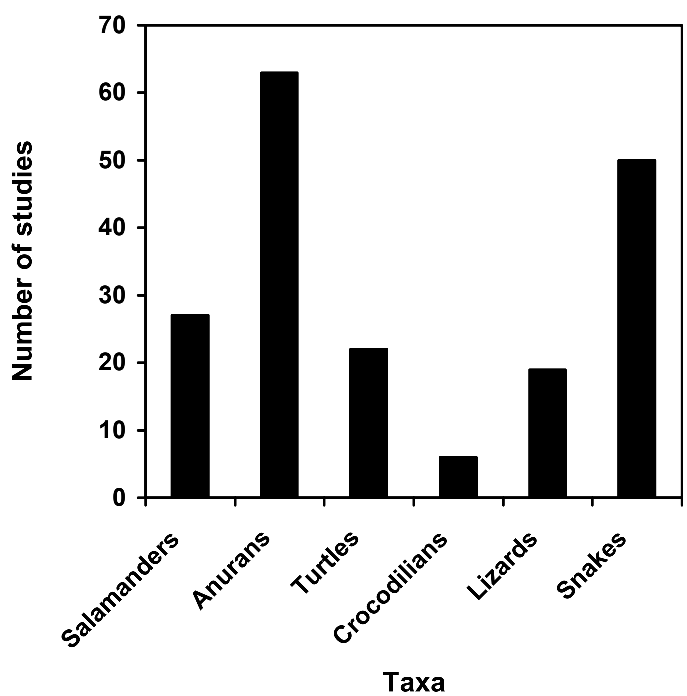

Figure 2. The number of studies (by taxa) in the road effects literature database documenting direct road mortality of amphibians and reptiles.

Salamanders

Many salamanders are susceptible to being killed on roads because they migrate between upland areas and wetland habitats to breed. Significant mortality may occur during mass migrations when animals must cross a road that separates these habitats. Breeding adults are subjected to crossing attempts twice (incoming and out-going), and young-of-the-year must cross roads during dispersal from the pond, resulting in significant mortality (Jackson 1996). Tiger salamander losses were the greatest during breeding movements in March along Nebraska's highways; 94% of road mortality across three years occurred during this month, accounting for 21.5% of total vertebrate mortality during March (McClure 1951). Average mortality rates ranging from 50 to 100% were reported for salamanders [red-spotted newt (*Notophthalmus viridescens viridescens*), spotted salamander (*Ambystoma maculatum*), and red-backed salamander (*Plethodon cinereus*)] crossing a paved rural road in New York (Wyman 1991). High incidences of road mortality of adult spotted salamanders occurred during breeding movements across Henry Street in Amherst, Massachusetts (Jackson 1996). Lodé (2000) recorded the road casualties of 196 salamanders (four species) on a 68.2-km section of motorway over a 33-week sampling period; peaks in mortality corresponded with migratory movements. According to a study conducted over eight years along a 20-km road section in Kouchibouguac National Park, Canada, less than 43% of the 618 salamanders encountered during road surveys were dead (Mazerolle 2004). Mortalities occurred during migratory movements that coincided with months of low park visitation.

Researchers monitoring a stretch of U.S. Highway 319 in Florida from September 1995 through September 1998 observed striped newt (*Notophthalmus perstriatus*), eastern newt, and mole salamander (*Ambystoma talpoideum*) carcasses (Means 1999). The migrations of adults and juveniles of these species were studied over a three-year period at a Florida pond located adjacent to this highway. In all three years the numbers of newts and salamanders migrating into the pond from the direction of the highway were fewer than expected, based on number of emigrants from the previous year. The author suggests that these species may be at risk due to decreasing numbers of individuals in the population and corresponding loss of genetic variation. The fact that individuals continue to breed in this pond shows that road mortality has not yet driven any of these species to extinction, but these data cannot currently provide any assessment of long-term effects.

Several studies document excessive rates of road mortality during movements prompted by certain weather conditions. Duellman (1954) observed 274 tiger salamanders over a 30-hour period crossing a 3.5 km stretch of Michigan highway during autumn under minimal temperatures; 83% of the individuals were discovered dead. The author suggests that the individuals appeared to move randomly in response to heavy rains. Clevenger et al. (2001) attributed an eruption of tiger salamander movement during August to a heavy rainfall event and warm temperatures. This study observed a minimum of 183 road-killed individuals over 5 days (4 of which were consecutive) distributed along a 1.05 km section of the Trans-Canada highway. Movement was further concentrated within a 300 m segment and in a northbound direction.

Anurans

The spatial distribution of essential resources and habitats, across the landscape may result in migrations of frogs and toads across roads and consequent high levels of mortality. Anurans accounted for 16.1% of the 6,723 vertebrates killed along 123,200 kilometers of Nebraska's highways traveled over 1941-1944; at least two species of toads made up 14.5% of that total and were the most frequently killed of more than one hundred species observed (McClure 1951). Carpenter and Delzell (1951) observed 873 road-killed anurans of 8 species in nine surveys along a 0.9-mile stretch of road in Michigan. In Britain, common frogs (*Rana temporaria*) experienced the greatest number of fatalities (409 individuals) of the 16 species (representing 3 taxa, without bird data) recorded during daily surveys along a 3.2-km route (Hodson 1966). Road deaths associated with breeding movements were estimated to account for 60% of the mean annual mortality. Over 84 nights of observation van Gelder (1973) recorded the deaths of 122 common toads along a 1.5-km section of road near breeding ponds in the Netherlands (van Gelder 1973). Cooke (1989) reported the mean annual mortality of 93 common toads near a breeding site in Ramsey, Cambridgeshire, England over a 21-year period. Over the course of one evening, Palis (1994) documented the mortality of 55 southern leopard frog (*Rana sphenocephala*) metamorphs (tadpoles that have recently gone through metamorphosis) emigrating across a 0.3-km segment of road adjacent to a pond in Florida. During the spring mating season in Ottawa, Canada, Fahrig and colleagues (1995) traveled 506 km (along three road segments) and counted a total of 1,856 dead frogs over six evening surveys. Anurans comprised 92.1% of vertebrate road-kills (32,000 total individuals representing 100 species) identified along Long Point Causeway in Ontario, with northern leopard frogs (*Rana pipiens*) accounting for 85.4% of the total casualties (Ashley and Robinson 1996). During one event in July 1996, more than 50 Couch's spadefoots (*Scaphiopus couchi*) were observed killed along a 3.84-km segment of road in Saguaro National Park; additionally, 279 road-killed toads, nearly all Sonoran desert toads (*Bufo alvarius*), were observed following one night of heavy rain (Kline and Swann 1998). A study conducted over a 33-week period on a motorway in France documented the road mortality of 466 anurans (five species), which accounted for 21% of all vertebrate casualties (Lodé 2000). In Kouchibouguac National Park, Canada, more than 54% of the 3,975 anurans encountered over eight years of road surveys were dead individuals (Mazerolle 2004).

Anurans experienced the greatest road mortality of any vertebrate taxon in a recent study conducted across a 3.2-km section of highway along Paynes Prairie, Florida, comprising 45.7% of all vertebrate road-kills with a peak in August of 30.2 individuals per day (Smith and Dodd 2003). In fact two species, green treefrogs (*Hyla cinerea*) and southern leopard frogs, accounted for 29% of the total vertebrate mortality (1,821 road-kill deaths of 62 species) over the yearlong survey. Based on the mean kill rate determined by 24-hour surveys, the authors estimate that 2,894 anurans were killed between 1998 and 1999 on the Prairie.

Several studies have strictly focused on the probability of individual amphibians being killed on the road. As reported in Reh and Seitz (1990), the estimated survival rate of toads crossing roads with 24-40 cars per hour varied from zero (Heine 1987) to 50% (Kuhn 1987). Hels and Buchwald (2001) calculated that the probability a crossing event would result in death ranged from 0.34 to 0.61 for roads with volumes of 3,207 vehicles/day, to as high as 0.98 for roads with volumes greater than 15,000 vehicles/day, depending on the various attributes of a given anuran species.

Turtles

A turtle's innate slowness increases the time spent crossing a road and therefore increases exposure to traffic (Gibbs and Shriver 2002). The literature suggests that this taxon may be most susceptible to traffic mortality when females exhibit peak movements. Turtles made up 4.0% of the 6,723 wildlife casualties observed along Nebraska's highways, with ornate box turtles (*Terrapene ornata*) representing half of those losses and suffering the heaviest during June

(McClure 1951). In northern Alabama, Dodd and colleagues (1989) drove a total of 19,045 km and counted 119 dead turtles during the summer of 1985; 85% of these deaths were of eastern box turtles. Wood and Herlands (1995) reported the road-kill deaths of 4,020 diamondback terrapin (*Malaclemys terrapin)* over six years of surveys along a road bisecting a marsh in coastal New Jersey. Ashley and Robinson (1996) recorded the road mortality of 716 turtles representing 5 species along a 3.6-km section of Long Point Causeway. Painted turtles (*Chrysemys picta*) experienced the highest mortality in May when hatchling dispersal from roadside nests resulted in 75% of the casualties. The mortality of snapping turtles was highest in September, with hatchlings accounting for 100% of the fatalities. A two-year survey along a 24-km segment of California Highway 58 documented the death of 36 desert tortoises, representing an average of one tortoise killed every 2.4 km per year (Boarman and Sazaki 1996). While monitoring a population of western painted turtles over the summer season in Montana, Fowle (1996) found 205 turtles of varying age and sex dead on the road and noted a major pulse of mortality during the nesting season. A survey conducted over a two-year period in central Ontario determined that annual road mortality of snapping turtles during their nesting period was 30.5% of all observed turtles (Haxton 2000). Smith and Dodd (2003) documented the death of 187 turtles, representing nine species, over the yearlong survey across Paynes Prairie. Aresco's (2003) study along a 1.2-km section of highway crossing Lake Jackson, Florida documented the highest rate of turtle fatalities at 9.7/km/day.

Crocodilians

Few studies have investigated the effect of traffic mortality on crocodilians. Harris and Gallagher (1989) concluded that traffic deaths are the major known source of mortality for some large, endangered species, including the American crocodile (*Crocodylus acutus*). Automobile collisions accounted for 46% of human-related mortality of this species (Gaby 1987). The road mortality study conducted across Paynes Prairie reports the death of 29 alligators over one year along the 3.2 km section of highway (Smith and Dodd 2003).

Lizards

Road studies on reptiles infrequently focus on lizards and documentation of road mortality within this taxon is therefore rare in the literature. This lack of evidence could be due to a deterioration of road-killed specimens, and potentially lower mortality rates for saurians due to their relative high speed and ability to cross roads faster. Furthermore, research indicates that certain species do not migrate seasonally and exhibit high site-fidelity within small home ranges, limiting their encounters with roads (Rutherford and Gregory 2003). When documented, total numbers of road-killed species sometimes are not listed exclusively, but rather are included within general reptile categories. Klauber's (1939) synopsis of road cruising in the southwest presents some statistical data on lizards observed on roads, but total numbers of dead individuals are not included. In particular, the banded gecko (*Coleonyx variegatus*) was commonly the most prevalent species observed during road surveys, so numerous that detailed data were often not recorded. The author does include a table indicating that at least 361 individuals were observed during 8 months of surveys. Fitch (1949) encountered a total of seven glass lizards (*Ophisaurus ventralis*) over the 8,480 miles traveled within west central Louisiana. McClure (1951) documented the road mortality of 95 lizards across Nebraska's highways, with heavy losses occurring during June. An incidental survey conducted over 19,041 kilometers in northern Alabama reported the road-deaths of 8 lizards (Dodd et al. 1989). Surveys conducted by Kline and Swann (1998) in Saguaro National Park between 1994 and 1996 documented the road casualties of diurnal lizard species and Gila monsters (*Heloderma suspectum*). Rodda (1990) found a total of 65 green iguanas (*Iguana iguana*) road-killed during a one-year survey in the llanos of Venezuela. The author states that the fact that the majority of these road-kills were male (51 of 65) and occurred throughout the breeding season during terrestrial movements has important implications for life history strategies. Sherbrooke (2002) documented a seasonal trend with a male-biased sex ratio in road-kill surveys of Texas horned lizards (*Phrynosoma cornutum*).

Snakes

Documentation of traffic fatalities of snakes is well represented in the literature. The development of quantitative road-driving as a sampling technique has contributed to revealing such mortality patterns. Klauber (1939) encountered a total of 1,970 snakes over the 52,403 kilometers traveled during the 1930's, 79% of which he discovered dead. Bugbee (1945) documented the mortality of 57 snakes in traveling across 416 kilometers of paved and gravel roads in western Kansas (only 11 individuals were observed on gravel roads); gopher snakes (*Pituophis catenifer*) comprised 54% of the specimens. Road counts conducted between March and June in western Louisiana documented 85 snakes representing 16 species, with 66 (72%) dead on the road (Fitch 1949). Driving across New Mexico, Campbell (1953, 1956) observed 305 dead snakes over 45,757 kilometers. Gopher snakes and Great Plains garter snakes were the reptiles most commonly road-killed along Nebraska's highways representing 11% of the total vertebrate casualties over three years (McClure 1951). In north central Alabama, Dodd et al. (1989) reported the incidental observations of 112 road-killed snakes over 135 days in 1985; surveyors drove a total of 19,041 kilometers, indicating a kill rate of 0.007 snakes per km traveled. Mendelson and Jennings (1992) conducted road surveys in Arizona and New Mexico and reported an observation rate of 0.066 snakes per kilometer driven; 53% of all snakes were dead. In Manitoba, the local road mortality of red-sided garter snakes migrating to and from their hibernacula is concentrated along a two-mile stretch of highway, and has been observed for more than 50 years (Krivda 1993). Sullivan (2000) conducted road-riding surveys in California, traveling a total of 4,424 km in the 1970's and 4,198 km in the 1990's. On average, 59% (n = 153) of the snakes encountered during the 1970's surveys were found dead on the road, compared to 54% (n = 237) during the 1990's. A study on the life history and ecology of massasauga rattlesnake populations conducted from 1979 to 1983 at the Squaw Creek National Wildlife Refuge in Missouri documented vehicular traffic as the most detrimental impact of refuge activities on this species (Seigel and Pilgrim 2002). Over this four-year study period, 23.2% (40 individuals) of the 172 snakes collected along roads that surround the refuge were found dead on the road. Road surveys along a defined 170-km route on the Eastern Snake River Plain in Idaho counted 258 snakes of four species between May and September of 2003; 93% of all snakes observed were dead (D. Jochimsen, unpub. data).

Studies that monitored short stretches of road, particularly adjacent to wetlands, documented high levels of mortality. Franz and Scudder (1977) observed 0.295 snakes per km surveyed over a 58-month period along Paynes Prairie State Preserve, and report a mortality rate of 90.4% along the 3-km survey route. Further surveys conducted from 1987 to 1990 along a 4.64-km section of this preserve revealed the road deaths of 13,000 snakes (Harris and Scheck 1991). Bernardino and Dalrymple (1992) studied an elevated two-lane highway that divides the habitats within the Pa-hay-okee wetlands region, located in the center of Everglades National Park. Seventy-three percent (approximately 763 individuals) of all snakes observed on the park's main road (11.5-km stretch) were either injured or dead.

The list of literature documenting road mortality of snakes spans over 60 years, yet the actual effects on snake populations have mainly been estimated using models or based on mean kill rates determined by survey efforts. Klauber (1972) estimated total road deaths in San Diego County, California at 15,000 snakes per year based on his survey efforts in the 1930's and increases in traffic levels. On New Mexico highways in 1951-1953, the mortality rate of snakes was estimated at 0.007 snakes/km/per year, yielding annual estimates of individual road-kills at 10,489, 13,840 and 25,744 respectively (Campbell 1953, 1956). These figures were calculated by determining a mortality rate per mile via quantitative road-cruising and then adjusting those totals for the additional miles covered by other established public roads in New Mexico. In Arizona, a four-year study conducted along a 44.1 km transect located on State Route 85 in the Sonoran desert reported the traffic casualties of 264 snakes, representing 20 species (Rosen and Lowe 1994). Incorporating these data into a computational model, the authors presented an algebraic method for estimating highway mortality of snakes. Using this model, the estimated death toll for these snake species is close to 2,383 individuals (13.5/km/year). Intensive mark-recapture efforts have yielded estimates of snake abundance at 695 individuals/km^2. Thus, over a four-year period along this 44.1-km study transect, the estimated impact of this highway mortality would result in a loss of all individuals within 65 m of the road edge. In another example, pedestrian surveys on rural roads in Florida estimated annual mortality at 12.8 snakes/km, based on survey results (228 individuals killed along a 6 km route over 2.8 years) (Enge and Wood 2002). The authors speculate that based on the total length of rural roads that traverse Florida (107,950 km in 1998) and their annual mortality rate, approximately 1.4 million snakes are killed yearly on rural roads alone across the state. Smith and Dodd (2003) report the highest rate of snake mortality on roads of any published study (to our knowledge) at 1.854 individuals per km surveyed (623 DOR snakes / 336 km). An additional 669 snakes were observed on day one of the surveys (not included in kill rate data) raising the death toll to 1,292 for the 52-week survey period. Based on these kill rate data, the authors estimated that 2,164 snakes died from traffic-induced injuries between 1998 and 1999 across Paynes Prairie. We advise that such estimates should be interpreted with caution due to variation in snake and traffic densities, as well as seasonal and geographic differences, but report these values to emphasize the potential impact that road mortality may have on snake populations.

In addition, episodic weather events may trigger mass movements of snakes that result in high levels of mortality over fine spatial and temporal scales. Following a period of extended rainfall, a total of 478 juvenile mudsnakes (*Farancia abacura*) was procured on a two-mile length of U. S. Highway 441 where it crosses Paynes Prairie State Preserve in Florida (Hellman and Telford 1956); the authors note that at least 223 (47%) of these individuals were discovered dead. Following a hurricane that occurred in 1941, Carr (1974) observed more than 700 snakes (at least 67% of which were dead) along the road and adjacent right-of-way. Flooding of the Mississippi River during the summer of 1993 in west central Illinois allegedly caused a movement pulse of snakes across the bordering highway that October (Tucker 1995). A total of 113 road-killed snakes was collected along a 54-km section over a period of 21 days; 76% (86 individuals) of which were observed on five dates alone. Total counts for the five-day period averaged 17.2 snakes/date compared to the 1.7 snakes/date average for the remaining 16 dates. The author attributes this unusual level of road mortality to habitat changes associated with the flood event that forced snakes to search for alternative hibernacula.

The literature provides ample evidence that road mortality results in significant losses of individuals for herpetofaunal taxa and lends reason to believe there might be a cause for concern in the sustainability of such levels. However, the manifold effects of roads extend far beyond wildlife vehicle collisions, and current research indicates that there is a much bigger picture to be evaluated. The following section elaborates on some of the indirect effects including aspects beyond immediate habitat loss and on-road mortality.

Indirect Effects of Roads via Habitat Changes

Roads affect wildlife indirectly through fragmentation of the landscape and alteration of physical conditions in the vicinity of roads (Forman et al. 2003). When discussing indirect road effects on herpetofauna, the information base becomes sparse as 1) research has been disproportionately focused on mammals and birds, and 2) indirect effects are more difficult to quantify, the documentation of which often requires long-term monitoring. Although not the focus of this document, we briefly discuss what is known about how roads affect habitat and the resulting indirect effects on amphibians and reptiles.

The combined outer limits of the manifold ecological effects involving species, soil, and water that extend beyond the road surface describe a “road-effect zone” (Forman & Deblinger 2000). The zone is irregular with boundaries dependent on the sequence of ecological variables, and disparate effect-distances due to nature’s directional flows such as slope, wind, and habitat suitability on opposite sides of a road (Forman and Alexander 1998). Two recent studies conducted in the Netherlands (Reijnen et al. 1995) and Massachusetts (Forman & Deblinger 2000) measured and estimated ecological variables to provide quantitative evidence for this definable “road-effect zone." The data suggest that the combined effects (thermal, hydrological, chemical and material pollutants, sediments, noise, invasion of roadside species, and human access affecting wildlife, fire, and sensitive habitats) extend outward for greater than 100 meters from the road edge. Based on the approximate width of this determined zone, Forman (2000) estimates that about one-fifth of the U.S. land area is affected ecologically by the infrastructure network with effect distances up to 800 meters. A recent study confirmed this estimate; analyses calculated that 16% of the total land area within the lower 48 states of the U.S. is within 100 m of any road type, 22% within 150 m, and 73% within 810 m (Riitters and Wickham 2003).

Problems arise when wildlife use road systems for movement, because roads are designed to serve as travel corridors for human purposes that do not provide the quality of environment necessary for wildlife health. Unlike natural corridors, roads frequently cross both topographic and environmental contours thereby fragmenting a range of different habitat types (Bennett 1991), extending the range of impacts to many wildlife groups possessing a diversity of life history strategies. Road construction results in habitat destruction with a replacement zone of intense human activity and subsequent alteration of wildlife habitats and behavior (Bennett 1991). The transformation of physical conditions on and adjacent to roads eliminates areas of continuous habitat and simultaneously creates edge effects that extend beyond the duration and extent of construction (Forman and Alexander 1998). These edge effects create habitat of compromised quality, which can result in wildlife death that actually occurs off-road as has been seen in several instances with indigo snakes (*Drymarchon corias couperi*) along the St. John’s River basin in Florida (R. Smith, pers. comm.).

However, certain species may benefit from edge habitat generated through fragmentation. Edge refers to the transition zone between original habitat and the matrix of altered habitat adjacent to it (Mitchell and Klemens 2000). Based on transect surveys and radio telemetry data, Klingenböck et al. (2000) discovered that lizards were abundant along forest edges among fallen trees with home-range centers located close to clearings used for thermoregulation. Individuals selectively used clearings adjacent to roads; the mean distance from a lizard's activity center to the nearest road was 17 meters ($\sigma = 2.2$ m). Research indicates that large-bodied lizards of the Amazon also benefit from habitat alterations that create open patches, because access to warm basking sites and foraging efficiency are increased (Vitt et al. 1998; Sartorius et al. 1999). However, both studies conclude that such disturbances may support high densities of these predators, which could have cascading effects on the prey assemblages of lizard fauna within forest patches.

Additionally, there are certain species that may use roads as a corridor for movement. Seabrook and Dettmann (1996) concluded that roads and trail systems facilitated the range expansion of cane toads (*Bufo marinus*), an introduced species, across Australia. Surveys revealed a significant increase in toad density along roads and vehicle tracks compared to transects within surrounding vegetation, and that the majority of tracked individuals actively used roads as dispersal corridors. Studies designed to examine the impacts of off-road vehicles on reptiles in Owyhee County, Idaho indicated that the density of most species increased with proximity to trails (Munger and Ames 2001; Munger et al. 2003). The authors suggest that this result is explained by the low recreational use, and the fact that trails clear surrounding cheat grass (*Bromus tectorum*), enabling swifter movements for reptiles through the area. Such effects are attributed to low-use trails only; substantial increases in use would likely result in the mortality of individuals attempting to follow the corridor.

Indirect impacts from road construction, such as runoff, hydrological changes, and sedimentation may occur beyond the immediate vicinity of road placement (Jones and Grant 1996). The sensitivity of amphibians, and in some instances reptiles, to surrounding environments has led to the suggestion of these taxa as indicators of environmental health (Gibbons et al. 2000). Yet, how this idea pertains to roads has only briefly been applied. For example, Mahaney (1994) found that petroleum contamination inhibited tadpole growth and prevented metamorphosis. We are not aware of any studies investigating toxicological effects of roads on reptiles. Due to the impervious nature of roads to rainfall, adjacent wetlands may experience elevated discharge and associated fluctuations in water levels, which diminish suitable habitat for breeding, foraging, and development of amphibians (Richter 1997).

Discharge diverted from roads may impact flow velocities, and the extent, depth, and frequency of flooding, all hydrologic factors that influence embryonic survival and breeding success (Richter 1997). Additionally, Richter and Azous (1995) found that wetlands experiencing water-level fluctuations of greater than 20 cm and flow velocities greater than 5.0 cm/sec had lower amphibian richness. Orser and Shure (1971) concluded that stream populations of dusky salamanders (*Desmognathus fuscus*) were negatively impacted by increased runoff in urbanized areas. Densities declined due to amplified soil erosion of stream banks, increased amount of particulate material suspended within the water column, and the scouring of stream channels, all factors attributed to excess runoff. Several additional studies have documented reductions of amphibian densities or populations of their invertebrate prey in streams experiencing sediment loading from roads (Richter 1997; Welsh and Ollivier 1998; Semlitsch 2000).

Maintenance activities associated with roads and surrounding edges may indirectly impact amphibians and reptiles. A few studies have investigated the potential effects that chemical application to road surfaces have on salamanders. Buech and Gerdes (U.S. Forest Service, Forestry Sciences Lab, Grand Rapids, Minn., unpub. data) observed hundreds of blue-spotted salamander (*Ambystoma laterale*) carcasses along a forest service road, and attributed the ultimate cause of death to desiccation from exposure to calcium chloride, which was sprayed periodically on the gravel road as a dust-control agent (deMaynadier and Hunter 1995). This observation prompted a pilot study that used trapping arrays to evaluate movement in response to application of the agent (D. Gerdes, pers. comm.). Based on captures, results suggested that the salamanders avoided recently treated areas (50% fewer successful crossings on treated versus untreated segments) (deMaynadier and Hunter 1995). In New Hampshire, embryonic survivorship of spotted salamanders was significantly lower within roadside pools compared to woodland pools (Turtle 2000). Sampling determined that highway runoff of sodium chloride (frequently used as a deicing salt) contaminated the roadside pools, implicating the agent as a factor in the reduced survivorship. Studies have concluded that road-side mowing has negative impacts on surrounding snake populations (massasauga, (Seigel 1986); and plains garter snake, (Dalrymple and Reichenbach 1984)) and recommended that managers schedule such operations to coincide during periods of inactivity for the animals. Mowing not only incurs direct mortality of individuals, but reduces cover availability, soil moisture, and prey densities, often rendering the habitat unsuitable for certain species (Kjoss and Litvaitis 2001).

Aside from chemical pollution, there is the potential that amphibians and reptiles could be negatively affected by factors not yet documented, such as physical or atmospheric pollution, predator-prey balance, and parasitism. These effects have been documented with other forms of wildlife, but it is not the objective of this document to elaborate on these specifics. A budding arena of investigation of road effects on herpetofauna is the study of impacts on movement and behavior. Although these topics are categorically included in indirect effects, we have chosen to designate them to another section for purposes of presentation.

Road Effects on Amphibian and Reptile Movements

Roads are landscape features that alter and fragment natural habitats, and as a result, may impede the movement of amphibians and reptiles. The barrier effect can occur when 1) animals are killed on the road in unsustainable numbers such that sufficient interchange of individuals does not take place; 2) the surrounding habitat quality is reduced such that animals cannot persist; or 3) animals behaviorally avoid the road contributing to isolation and habitat fragmentation.

Vehicular traffic alters the environmental conditions of habitat adjacent to roads via noise, enhanced lighting, and emissions resulting in the modification of behavior and movement patterns of certain wildlife species (Bennett 1991). The effects of traffic noise and vibrations on vertebrates include hearing loss, increase in stress hormones, altered behaviors, and interference with communication during breeding activities (Forman and Alexander 1998). All of these effects may disrupt cues necessary for orientation and navigation during migratory movements, especially for species that rely on such cues for sustaining ecological behaviors (e.g. breeding frogs and salamanders, and the orientation of hatching sea turtles towards the ocean). Amphibians and reptiles suffered physiological and behavioral hearing loss and misinterpretation of environmental acoustical signals when exposed to off-road vehicle noise (Brattstrom and Bondello 1983). Background noise often results in modification of calling behavior in males and may impair the ability of females to discriminate among call types and to discern location of calling males during breeding migrations (Schwartz and Wells 1983; Schwartz et al. 2001). Exposure to artificial light can cause nocturnal frogs to suspend normal foraging and reproductive behavior and remain motionless long after the light has been removed. (Buchanan 1993). Olfaction plays a primary role in amphibian migration and orientation (Duellman and

Trueb 1986; Oldham 1967) and it is possible that environmental cues may be obscured by emissions or runoff from vehicles, or from characteristics of the road substrate (Shine et al. 2004). Vehicles can also force wildlife to adapt their behavior either by posing an impenetrable barrier, in which animals selectively avoid the road, or through influences on crossing behavior. Studies at the Savannah River Ecology Laboratory in Aiken, S.C. demonstrated a high propensity for three snake species (black racer, *Coluber constrictor*; rat snake, *Elaphe obsoleta*; and canebrake rattlesnake, *Crotalus horridus*) to immobilize in response to a passing vehicle, prolonging the amount of time it takes to cross a road and increasing the risk of mortality (Andrews 2004). Although the frequency of such immobilization behavior correlates with natural predator responses, this response occurred at significant rates even in species with the ability and instinct to rely on flight (i.e., black racer).

Roads that fragment natural habitats may alter the size, shape, and spatial arrangement of habitats, which in turn affects wildlife dispersal patterns (Fahrig and Merriam 1994). Roads appear to be an important anthropogenic landscape component that hinders amphibian movement, as demonstrated in a study assessing amphibian movement in response to forest edges, roads, and streambeds in Connecticut (Gibbs 1998a). Amphibians (salamanders and frogs) captured at drift fences located at the forest edge were compared to captures located in the forest interior to determine relative permeability of forest edges to amphibian movement. The author used the term permeability to reflect the magnitude of reduction or increase in amphibians' movement at ecosystem edges relative to continuous forest. Forest edges associated with roads were less permeable (0.3) than forest edges associated with open habitat (0.9) suggesting that some woodland amphibians will cross substantial areas of open land during breeding migrations, if physical barriers such as a road don't inhibit their movement. Forest roads apparently can serve as a partial filter to the movements of some amphibian species.

Movement data collected on eight species of amphibians within a Maine forest suggest that barrier effects from roads may vary depending upon the specific type of movement being made (deMaynadier and Hunter 2000). The data reflect that a greater proportion of natal dispersal movements occur across roads (22.1%) than either migratory movements (17.0%) or home-range movements (9.2%). Salamander (i.e., *Ambystoma* spp., red-backed salamander, and red-spotted newt) movement was inhibited across a wide forest road (12 m) with heavy use (300 vehicles/day), and species abundance was found to be 2.3 times higher at forest control sites than at roadside sites. In contrast, anuran habitat use and movements were generally unaffected by the wider logging roads (deMaynadier and Hunter 2000).

Another way that roads can serve as a barrier to movement is by the mechanism of selective (i.e., genetic or behavioral) road avoidance. Behavioral avoidance has been documented in wildlife groups ranging from invertebrates (snails, Baur and Baur 1990) to mammals (wolves, Thurber et al. 1994). Gibbs (1998a) observed behavioral road avoidance of amphibians in New England. Radio-implanted tiger salamanders tracked during terrestrial emigrations from breeding ponds moved all directions within surrounding forest habitat, but avoided open habitats including paved roads, commercial areas, and grassy fields (Madison and Farrand 1998). Roads have also been shown to impact desert tortoise populations through restriction of movement patterns (Boarman and Sazaki 1996). We are aware of one study concerning road avoidance by lizards. Although data revealed that land mullets (*Egernia major*) selectively used edge-habitat adjacent to roads, radio-tracked individuals actively avoided crossing the road surface (Klingenböck et al. 2000).

Road avoidance by snakes has been noted from incidental observations (timber rattlesnake, Fitch 1999; Sealy 2002), and both single-species assessments (massasauga, Weatherhead and Prior 1992; red-sided garter snakes, Shine et al. 2004) and interspecific comparisons (9 species; Andrews 2004). In Ontario, massasauga rattlesnakes were captured on roads disproportionately relative to habitat composition within Bruce Peninsula National Park (0.86% of captures/ 29.1% of habitat type), yet radio-tracked individuals showed a strong affiliation for wetlands and coniferous forests seldom using roads or trails (only 2% of relocations) (Weatherhead and Prior 1992). Andrews (2004) documented significant levels of variation among species avoidance, although levels were higher than initially hypothesized for snakes that are known to cross roads. A correlation was found between propensity to cross the road and body length in that smaller snakes had a greater tendency to avoid the road. It is suggested that this finding is likely due to natural behaviors of smaller snakes to avoid open spaces. Enge and Wood (2002) also speculate that small secretive species that often occur in high numbers within habitats adjacent to roads may be reluctant to emerge onto the road surface. Genetic avoidance has not been adequately documented due to the lack of long-term studies on this topic. However, the increasing prevalence of literature concerning behavioral avoidance implies that if this behavior is sustained, there will eventually be genetic-level repercussions.

In summation, we are discovering that road impacts on herpetofauna are complex at all levels (taxon, species, individual), and therefore, the potential for roads to act as barriers, or filters, to amphibian and reptile movement requires further research.

Road Effects on Amphibian and Reptile Populations

The negative impacts of roads on amphibian and reptile populations are often underestimated (Vos and Chardon 1998) for several reasons. The various effects of roads (both direct and indirect) on populations transpire at different rates; for example, effects such as habitat loss result in immediate declines of populations, while the consequences of reduced connectivity may not be realized for several generations (Forman et al. 2003). Furthermore, the natural variability that occurs in amphibian and reptile populations requires the incorporation of broad temporal and spatial scales to adequately study road effects. Breeding populations of salamanders and frogs, for example, fluctuate by as much as 1-2 orders of magnitude among years (Pechmann et al. 1991, Blaustein et al. 1994) due to variation in abiotic factors that regulate populations of larvae, adults, or both (Wilbur 1980). Findlay and Bourdages (2000) suggest that the full effect of roads on herpetofaunal populations could take decades to become apparent if the initial populations were high. For example, in a population of Columbia Spotted Frogs (*Rana luteiventris*) in Yellowstone National Park, breeding did not cease at a roadside pond until about 20 years after the relocation of a highway separated the breeding pond and summer foraging area from a stream used for hibernation (Patla 1997). Finally, effects that roads have on the mating success of reptiles are not yet understood. However, in some reptile species, males are more likely to be killed than females (snakes, Bonnet et al. 1999; lizards, Sherbrooke 2002), with the converse being true for turtle species (Steen and Gibbs 2004). Both incidences can skew sex ratios and therefore the efficiency with which animals can find a mate.

Demographic Effects

Roads may impact population size and isolation of amphibians and reptiles through the direct removal of individuals, the creation of edge habitat or features that attract individuals to roadsides, fragmenting continuous habitat, and modifying behaviors that make animals less likely to attempt or successfully cross the road. Relatively few studies address the effects that roads have on amphibians and reptiles at the population level. It is even more uncommon to have the data sufficient to relate road-kills to the spatial organization of these populations. Such questions prove difficult to address because corresponding data on species abundance across large spatial and temporal scales are generally not available. In a review on roads and their major ecological effects, Forman and Alexander (1998) conclude that vehicles are prolific killers of terrestrial vertebrates, but with the exception of a small number of rare species, road-kills have minimal effect on overall population size. However, in our review of the literature we have found documentation of amphibian and reptile population declines as a result of direct road mortality and isolation.

The construction of new roads, or the widening of existing ones has the potential to decimate adjacent populations. Klauber (1939) presents evidence that the opening of a short cut off the San Diego-Tijuana highway resulted in the decline of snakes in the surrounding area. Surveys revealed 16 dead snakes along a 1.3-mile road segment one year after the road opened with marked decreases in numbers over the following four years. In Virginia, the conversion of cypress ponds into residential areas and a four-lane highway endangered an isolated population of chicken turtles (*Deirochelys reticularia*), with traffic-related mortality playing a role in the continued loss of individuals (Buhlmann 1995; Mitchell 1994). Surveys conducted just one year after the construction of a motorway in France documented considerable road casualties of vertebrates (on average 14.52 animals/day/100km) (Lodé 2000).

The impact that road mortality has on populations of long-lived species that exhibit a low annual recruitment, delayed reproduction, and high adult survivorship could result in population declines. For example, Doroff and Keith (1990) determined that box turtle populations could not sustain the annual net loss of even one adult. This suggests that the high mortality rate of these species reported by road studies (McClure 1951; Dodd et al. 1989) could have detrimental impacts. Transect surveys conducted in the vicinity of California Highway 58 to measure desert tortoise activity signs, an index of population density, revealed a zone of reduced activity within 0.4 to 0.8 km from the highway edge (Boarman and Sazaki 1996). Off-road vehicle use has also been linked to population declines of the desert tortoise (Bury 1980), and as of July 3, 2004, an additional 1,500 miles of trails that pass through critical habitat in the Mojave Desert were approved for ORV recreational use (Wildlands Center for Preventing Roads, Skid Marks Issue #85). Similarly, according to population estimates, densities of western painted turtles were depressed within close distances of the highway (Fowle 1996).

Declines have also been documented in several species of snakes with similar life history characteristics. Rudolph et al. (1998) plotted locality data for timber rattlesnakes on Texas State Department of Highways and Public Transportation General Highway maps and searched for correlations of presence with road density. The data suggested that roads and associated vehicular traffic have influenced the current distribution of this species by restricting activity to areas of low road density, which in turn has lead to increased demographic isolation. Results from a trapping survey conducted in east Texas revealed that snake populations are reduced to a level of greater than 50% up to a distance of 450 m from roads with moderate traffic volume (Rudolph et al. 1999). These data suggest that a substantial proportion of the expected snake community has been eliminated across the landscape due to vehicle-related mortality. Such on-road mortality is also implicated in the local extirpation of timber rattlesnake populations and significant losses of Louisiana pine snakes (*Pituophis ruthveni*) in eastern Texas (Rudolph et al. 1998). A monitoring study conducted on eastern massasauga rattlesnakes between 1999 and 2000 in Illinois revealed an estimated population size between 65 and 72 individuals. Vehicular traffic accounted for 60% of the 28 known cases of mortality that occurred during August. Such high levels of mortality could further contribute to the endangered status of this species (D. Shepard and C. Phillips, pers. comm.). Data from a survey of snake communities in Florida (Enge and Wood 2002) revealed that four species of large-bodied snakes were captured three times more frequently in drift fence arrays located in continuous habitat patches than on roads through fragmented areas. Conversely, one study detected similar abundances of snakes along a 19-km transect of road surveyed in the 1970's and 1990's, with the exception of gopher snakes, despite increased traffic levels, off-road vehicle use, grazing, and human predation (Sullivan 2000).

Additionally, certain features within the "road-effect zone" may be appealing to amphibians and reptiles, creating a potential drain on populations adjacent to roadsides. Examples include standing water in ditches, warm road surfaces providing opportunities to thermoregulate, and changes in habitat associated with road edges. Forest roads may serve as an attractant through the creation of herpetofaunal habitat by blocking stream flow or by creating depressions (e.g. tire ruts) that may fill with rainwater. Amphibian species will sometimes use these areas for hydration or breeding. Generally, pools and road-side ditches are only temporary and successful egg and larval development may be rare (Richter 1997). In addition, the tires of passing vehicles can potentially kill any life attracted to these pools or present in ruts (D. Jochimsen, pers. obs.). Main and Allen (2002) detected road-kill aggregations of amphibians and turtles adjacent to water-filled ditches, and the greatest number of snakes observed during the 1973-1977 monitoring study across Paynes Prairie (Franz and Scudder 1977) was associated with road sections bordered by permanent water in ditches. The fact that roads serve as an attractant has an extended effect in that predator concentration could occur as a consequence of a prey base that is using edge habitat along the road. For example, small mammals have been shown to disperse and reside along road corridors (Getz et al. 1978), which could result in subsequent attraction of their predators (e.g., snakes). Also, we have observed mass numbers of western toad tadpoles in deep ruts on a forest road in Idaho, along with two terrestrial garter snakes that were actively foraging on the young anurans (D. Jochimsen, pers. obs.). Research suggests that anurans may use ditches as corridors when traversing long distances between local populations (Reh and Seitz 1990; Pope et al. 2000). The Organ Pipe shovel-nosed snake (*Chionactis palarostris organica*), endemic to Organ Pipe Cactus National Monument in Arizona, is deemed highly predisposed to road mortality and clusters of dead individuals were observed along road edges modified with thickets that may have served as an attractant (Rosen and Lowe 1994). Hódar et al. (2000) reported that common chameleons (*Chamaeleo chamaeleon*) inhabiting an area undergoing extensive development in southern Spain selectively used habitats adjacent to roads and orchards. Individuals were not observed within patches of natural vegetation due to a higher density of shrub cover and lack of tall plants preferred by this species. Although the chameleons benefit from these land uses, they are one of the most susceptible species to road mortality (Caletrio et al. 1996) and suffer from illegal collection and nest destruction by ploughs.

Studies designed to evaluate changes in the species composition of snake communities over time related the occurrence of new species and declines of others to changes in vegetation type and cover along roadsides. Comparison between two studies across Paynes Prairie (Franz and Scudder 1977; Smith and Dodd 2003) suggests that two new species observed in 2000, (corn snake (*Elaphe guttata*) and rough green snake) and a three-fold increase in the number of Florida cottonmouths occurred in response to habitat changes adjacent to the road edge. Shifts in the abundance of snake species along highways within the desert grasslands of Arizona and New Mexico were correlated with the succession of plant communities (Mendelson and Jennings

1992). Tuberville et al. (2000) documented the occurrence of southern hognose snakes (*Heterodon simus*) within disturbed habitats. The apparent decline of this species across much of its range (Tuberville et al 2000) raises concern about the apparent attraction to roadside areas due to the increased risk of road mortality associated with frequent use of such habitats. In fact, a high proportion of the locality records compiled by the researchers, were based on specimens found on roads (both alive and dead). A comparison of snake communities inhabiting xeric upland habitats in Florida via drift fence and road surveys revealed differential captures of several species (Enge and Wood 2002). The rough green snake, southern hognose snake, and Florida brown snake (*Storeria dekayi victa*) were frequently observed during road surveys but seldom trapped in drift fences located in intact sandhill and xeric habitats in the 1990's, suggesting that these species are attracted to roadside conditions. In fact, these species alone comprised 43% of documented road mortality despite that 18 total species were recorded throughout the survey period. Furthermore, 46% of the observed southern hognose snakes were found on road segments bordered by disturbed habitats, although such segments covered only 21% of the survey route.

Amphibian and reptile populations are dynamic and therefore experience natural fluctuations and are dependent on the maintenance of dispersal corridors and "landscape linkages" in human-altered environments (Gibbs 1998a). Vos and Chardon (1998) emphasize that for terrestrial species, such as amphibians and reptiles, isolation can be regarded as a combination of distance between habitat patches as well as any resistance to movement between these patches that occurs across the landscape. Extinction and recolonization rates for habitat patches can be related to their connectivity (Merriam 1991; Laan and Verboom 1990) and species characteristics, such as dispersal ability, the number of dispersers (Laan and Verboom 1990), in addition to seasonality and unpredictable weather conditions. The road network potentially contributes considerably to the resistance between patches (Bennett 1991) and therefore may serve to isolate wildlife populations. The exchange of individuals between habitat patches will decrease due to the aforementioned reasons, which may result in lower recolonization rates and increase the extinction risk of local populations (Vos and Chardon, 1998).

Research demonstrates that habitat fragmentation impinges on the persistence of populations and abundance of individuals. Due to information availability and a likely lower tolerance of amphibians to the loss or isolation of subpopulations, the following information will be heavily biased toward amphibian studies. Several studies have documented the absence of amphibian species in small or isolated habitat patches, including the pool frog (*Rana lessonae)* (Sjögren 1991, 1994), the common frog (Loman 1988), the tree frog (*Hyla arborea)* (Vos and Stumpel 1996), and the moor frog (Vos and Chardon 1998). Sjögren (1991) hypothesized that amphibian populations occur as natural metapopulations due to the historical, discontinuous distribution of wetlands across the landscape. Interpopulation proximity and connectivity are considered important for the persistence of a northern metapopulation of the pool frog (Sjögren 1994). Such populations may therefore be negatively affected by the presence of roads, in that landscape connectivity is reduced. Fahrig et al. (1995) concluded that the abundance of roadside anuran populations was negatively correlated with traffic volume in Ottawa, Canada, which suggests that an increased number of road fatalities, as well as increased isolation, have impacted these populations. Conversely, a road-cruising study conducted in Kouchibouguac National Park, Canada, did not detect a decreasing trend in amphibian abundance over eight years of surveys, despite high levels of on-road mortality (Mazerolle 2004). The author explains that this result may be due to the resiliency of local amphibian populations, moderate traffic volume, limitations of the sampling technique, or the combination thereof, and cautions that the effects roads with low traffic loads should, however, not be underestimated. Vos and Chardon (1998) determined that roads negatively affect the persistence of anuran populations, and that the probability of the moor frog occupying a pond was negatively correlated with both traffic and road densities.

Several studies demonstrate that a species' ability to persist in fragmented landscapes is dependent on its ecology. For example, habitat generalists may be able to better adapt to altered conditions than species that are specialists (geckos, Sarre et al. 1995; snakes, Kjoss and Litvaitis 2001). Research indicates that the persistence of many anuran populations is dependent on recruitment and dispersal of juveniles (Sinsch 1992; Semlitsch 2000; Hels and Nachman 2002; Joly et al. 2003). Using a simulation model, Hels and Nachman (2002) determined that the probability of subpopulation persistence of spadefoot toads (*Pelobates fuscus*) increased from 0 to 0.6 when the annual survival rate of juveniles was enhanced from 0.35 to 0.40. This particular metapopulation of toads persists in a landscape fragmented by a road in Denmark. Persistence probability was highest for the subpopulation comprised of juveniles with the highest estimated rates of survival. In addition, a 20% decrease in the number of individuals dispersing to a pond distinctly reduced the persistence probability for subpopulations isolated by the road.

The site-specific, long-term effects of road construction on amphibian and reptile populations have been infrequently documented. In Yellowstone National Park, demographics and spatial relationships of a Columbia spotted frog population were studied in the 1950s (Turner 1960) and re-investigated in the 1990s, with monitoring continuing through 2002 (Patla 1997; Patla and Peterson 1999). The study area was modified by development in the years intervening between the two investigations, including a major road constructed in the early 1970s. The road was located between a pool where spotted frogs bred and a permanent stream where frogs over-wintered, cutting across a migration corridor linking these areas. Based on mark-recapture population estimates, the area's frog population declined about 78% between the mid-1950s and the mid-1990s. Spatial distribution was altered, with the 1990s population largely dependent on breeding, foraging, and over-wintering habitat clustered on one side of the highway. Breeding ceased at the pool nearest the highway after 1994. While a small number of frogs continued to cross the road-way at the historic location, mass migrations observed in the 1950s (Turner 1960) no longer occurred by the 1990s (Patla 1997; Patla and Peterson 1999). Results obtained through a 25-year assessment of amphibian and reptile populations within the John F. Kennedy Space Center in Florida showed that all but one species, the eastern hognose snake, present during the 1970's surveys were detected again during the 1990's (Seigel et al. 2002). However, data showed a quantifiable decrease in the total count of snakes as well as changes in species composition, with a notable decline in cottonmouths and Florida green water snakes (*Nerodia floridana*), found during road surveys conducted along a 19.3-km segment. The authors mention habitat loss, fragmentation, and cumulative road mortality as plausible factors behind these changes.

Roads have also been shown to influence population structure in reptiles, specifically sex-ratio and the composition of certain life stages. In New Hampshire in a study of painted turtles, a positive correlation existed between proportion of males and adult abundance in a pond and road density within 100 m (Marchand and Litvaitis 2004). The number of injuries observed on female turtles was also positively correlated with road density. Male-biased sex ratios were again observed in central New York in populations of painted turtles and snapping turtles (Steen and Gibbs 2004). Neither Steen and Gibbs (2004) nor Marchand and Litvaitis (2004) found that roads immediately affected abundance, however, the consistency of all three studies lends credible attention to the finding that female turtles are killed disproportionately on roads, which could lend to population instability. Conversely, with snakes, roads have been found to kill a higher proportion of males (Bonnet et al. 1999, Sealy 2002, K. Andrews and J. W. Gibbons, unpub. data), which could also have a destabilizing effect as seen with the turtles. A greater mortality risk for males has also been seen with Texas horned lizards (Sherbrooke 2002). Lastly, Bonnet and colleagues (1999) also found a higher likelihood of neonatal road mortality during post-hatching dispersal. Little is known regarding how susceptibility to road impacts varies across life stages of herpetofauna.

Genetic Effects

Metapopulation dynamics and dispersal play a key role in structuring amphibian and reptile populations. These taxa generally have restricted distributions and small population sizes and, therefore, are more vulnerable to local extinction due to stochastic changes. The barrier effects created by roads may result in the reduction of genetic diversity and gene flow due to the increase of inbreeding, increased risk of local extinction due to population dynamics and catastrophic effects, and a decrease in the ability to recolonize (Rodriguez et al. 1996). However, despite the significance of these potential effects, there have been few studies that have empirically studied genetic effects due to roads. The studies that have addressed this issue have supported the hypothesis that roads decrease genetic diversity and gene flow. For example, the average heterozygosity and genetic polymorphism of local common frog populations in Germany were reduced due to separation by highways (Reh 1989; Reh and Seitz 1990). The average percentage of all gene loci varied between 0 and 4% heterozygosity, and these populations appeared to be highly inbred as a result of the inability to exchange genetic material. Reh (1989) concluded that even when amphibian populations were less than 4 km apart, roads have a negative influence on gene flow between populations. However, genetic exchange was possible between populations separated by 3-7 km of grassland, or 5-10 and up to 40 km of ditches. Hitchings and Beebee (1998) also found lower genetic diversity and higher inbreeding in urban populations of common frogs as compared to rural areas. Similarly, habitat limitations due to the presence of roads in an urban environment resulted in the reduction of genetic diversity and fitness in common toad populations in Britain (Hitchings and Beebee 1998; Scribner et al. 2001).

Gene flow also appears to be significantly constrained by the presence of urban areas and roads. In common frogs, population subdivision (based on F_{ST}) was more than double among urban sites than rural sites, a highly significant difference (Hitchings and Beebee 1997). Rowe et al. (2000) also hypothesized that urban areas would create genetic barriers for natterjack toads (*Bufo calamita*). They tested this by adding "extra" distance to the overall geographic distance if an urban area was between two sites, and then testing the correlation between genetic distance (based on microsatellites) and the weighted distance. Their results did support their hypothesis, as the genetic data did correlate better with geographic distance with two kilometers added for the negative barrier effect of the urban environment than with geographic distance alone. Vos et al. (2001) also used microsatellites to investigate gene flow in the moor frog. However, their study was unique in that they focused specifically on roads and developed a more precise weighting factor for geographic distance, in which they used the length of the roads relative to the distance between the sites to add to the geographic distance. They obtained the same result as the natterjack toad study, demonstrating that this weighted distance had a stronger correlation with genetic distances. However, despite this, there was not high subdivision among the populations. The authors speculated that this result might be a historical signature, and that disruption of gene flow by roads may be too recent to be detected. It is unclear whether this is a likely explanation, as microsatellites are generally quite sensitive genetic markers, and fragmentation of the study area had existed for more than sixty years. For example, a fifty-year old highway was shown to cause genetic differentiation in a population of voles, based on microsatellite markers (Gerlach and Musolf 2000).

While there is great potential for genetic studies to provide insight into how roads affect populations, relatively little has been done on this topic. The few studies conducted have focused on European anurans. Because the full impacts of roads may take years to become apparent (Forman et al. 2003), direct methods such as mark-recapture and drift fences may not be as effective as genetic analyses for detecting changes in population structure due to fragmentation. Clearly, this is a crucial future direction for herpetological road studies.

Road Effects on Species Richness

Variables measured across the landscape, such as density of roads and the degree of intact terrestrial buffer surrounding breeding ponds, have been correlated with species richness of herpetofauna (Dickman 1987; Findlay and Houlahan 1997; Halley et al. 1996; Knutson et al. 1999; Lehtinen et al. 1999; Vos and Stumpel 1996). Decreases in landscape connectivity via habitat fragmentation and loss can affect amphibian assemblages. Distance to the nearest neighboring pond has been shown to influence species richness and populations and is likely linked to amphibian dispersal ability (Vos and Stumpel 1996; Halley et al. 1996). In southeastern Ontario wetlands, herpetofaunal species richness is negatively correlated with paved road density (Findlay and Houlahan 1997). Herpetofaunal biodiversity showed a strong positive correlation with the proportion of forest cover and wetland area, both attributes that may be negatively affected by density of paved roads. Surveys assessing the effects of landscape composition and habitat fragmentation on wetland amphibian assemblages in Minnesota (Lehtinen et al. 1999), Iowa and Wisconsin (Knutson et al. 1999) revealed similar trends. The most consistent result across all amphibian groups was a negative association with the presence of urban land. Amphibian species richness was lower with greater wetland isolation, road density, and the overall proportion of urban land-use within the landscape. Species richness of amphibians and reptiles within patches that are delimited by roads, walls, or other artificial barriers increased with patch area, but declined away from sources of permanent water within the city of Oxford (Dickman 1987). Consistent with the species-area hypothesis (MacArthur and Wilson 1967), Kjoss and Litvaitis (2001) observed lower species richness of snakes on small patches of habitat, all of which were located within road corridors. As with populations, cumulative effects that roads may have on the biodiversity of an area may take decades to become apparent. Findlay and Bourdages (2000) discovered that current species richness in wetlands corresponded with estimates of road density from 30 to 40 years ago, rather than recent patterns.

Methods to Minimize the Ecological Effects of Roads

Various measures may be applied to prevent, mitigate for impacts of roads on surrounding habitats and wildlife. Many methods may be implemented once a conflict between wildlife and infrastructure is recognized; however, we emphasize the usefulness of proactive planning. Consideration and evaluation of measures during the process of road planning addresses potential environmental impacts and may reduce construction costs (Seiler and Eriksson 1995; Forman et al. 2003). In fact, many European countries have established national policies that require ecological evaluations of potential projects (Seiler and Eriksson 1995), and the state of Florida has been a leader in proactive planning through the development of an interagency “Efficient Transportation Decision Making Process” (ETDM) (White and Ernst 2003). The following sections provide examples of the various methods used to manage the ecological effects of roads.

Avoidance of Ecological Impacts

Identification of potential problem areas may be determined before road construction takes place. Geographic Information Systems (GIS) may be used to overlay a map of the proposed project with maps of critical habitat and models identifying wildlife corridors to locate areas of potential overlap (Clevenger et al. 2002). Florida Department of Transportation (DOT) takes this concept a step further through the creation of Environmental Technical Advisory Teams (ETAT) that evaluate potential projects according to a checklist of various criteria from social to environmental impacts (White and Ernst 2003). In any case, such maps may then be used to suggest alternative routes for the road project in areas of minimal impact. While many states are in the process of developing such resources, project officials may look to conservation plans developed for certain species or research concerning species ecology prior to road construction in attempts to ensure the protection of vulnerable habitats and wildlife (White and Ernst 2003).

An effective procedure to prevent road mortality involves closing sections of roads during selected periods of the year to allow for movements that are often predictable in certain species (Podloucky 1989; Seigel 1986). This method allows for the maintenance of traditional migration routes without alteration of the surrounding habitat, reduces the numbers of road casualties, and decreases the overall noise experienced by individuals moving through road-side habitats. The city of Richmond, Virginia closes a half-mile section of Riverside Drive when evening conditions are conducive to movement to ensure the successful breeding migrations of individuals from an isolated population of spotted salamanders to road-side ponds (S. F. Spear, pers. comm.; Richmond Times Dispatch 2004). Although this population inhabits James River Park, the support of the city and local residents was needed to sanction the public road closure, granted in 2002. Ralph White, park manager, obtained support for the closure through outreach efforts that provided evidence that road mortality and urban developments were threatening the persistence of this population. The annual event is publicly recognized, with newspaper coverage and citizens eager to witness the migration. The US Forest Service initiated a multiple-week closure of a 2.6-mile section of road through La Rue – Pine Hills Research Natural Area, Illinois in 1972 to allow for snake migrations between limestone bluffs and nearby swampland bisected by the road (Ballard 1994). Based on six years of data, Ballard recommended two-month extensions to the closure dates to protect a greater number of migrating organisms. A total of 19% of all amphibians and 22% of all reptiles captured through various survey methods were found crossing the road, or using adjacent areas as habitat. The Forest Service complied with the recommendation, despite ongoing protests from sportsmen (Tribune Outdoors 1997). Since 1993, Tilden Regional Park annually closes a section of road from November through the following spring to allow for mating migrations of California newts (*Taricha torosa*) (The Daily Californian 2003; Berkeley Daily Planet 2004). One problem associated with road closures is the facilitation of illegal collection of animals for pets or pet trade, because humans are aware of the precise location of migration corridors (Tribune Outdoors 1997).

Several other methods designed to avoid impacts involve the installation of signs that either caution motorists or restrict traffic speed. Road signs may be erected to warn motorists of these migrations and urge caution when traveling near areas prone to high incidence of road mortality on these species (Seigel 1986; Jackson 1996). For example, in Manitoba, snake crossing – speed reduction signs were installed at the north and south ends of the migratory corridor to alert the public to the need to reduce speed in this portion of the highway (Canadian Amphibian and Reptile Conservation Network website). Monitoring of snake response to the reduced speed identified that animals crossing the highway can avoid being hit by cars traveling at a slower speed. Unfortunately, most motorists did not heed the speed reduction request and as a result the benefits of this technique were minimal. The signs will continue to be installed during migratory periods to make the motoring public aware of the need to reduce speed through the corridor. Alternate breeding ponds may be constructed in efforts to limit encounters with roads during migration (Podloucky 1989). Additionally, local rescue efforts may be carried out by physically moving amphibians and reptiles safely to the other side of a road (Langton 1989).

The physical removal of animals from habitats within range of an impending development is a method used to minimize mortality during road construction. Local conservationists and faculty members at the University of California at Davis volunteered to collect and care for western toads during construction efforts that removed topsoil from a breeding pond, and then returned animals following completion of the project (Case viewed at Critter Crossings website). In 1989, researchers collected a total of 300 Hermann's tortoises (*Testudo hermanni*) living within the development corridor of a future highway through southern France (Guyot and Clobert 1997). These individuals were then placed within semi-natural enclosures through the duration of construction, marked along marginal scutes (for later identification), and eventually returned to an area south of the new highway. Researchers conducted surveys along the highway corridor three and four years post construction and observed 70 relocated tortoises (a total of 595 individuals). Based on mark-recapture techniques, the rate of annual survival was estimated at 78%, while the effects of relocation reduced first-year survival to 51%. These rates are comparable to other studies that have examined the effect of relocation on survival of turtles, and indicate that mortality rates are highest in the years directly following relocation, but might be sustainable over the long term.

Road removal and the creation of compensatory habitats are other options designed to avoid road impacts on the environment, but will not be addressed in this document.

Road-Crossing Structures

A variety of road-crossing structures have been implemented to mitigate the impacts of road systems on wildlife movement and mortality (Jackson 1999). The general function of a crossing structure is to provide safe passage for an animal across the road and to provide connectivity between habitats adjacent to the road (Forman et al. 2003). These passages may either be constructed for this sole purpose or modifications of existing structures, and selection of a specific design is usually determined by the target species or groups expected to use them. It is critical that the ecology of surrounding wildlife be considered when attempting to create movement corridors. For example, in his review, Richter (1997) explains that migratory direction taken by amphibians varies by life-stage and species. Table 1 provides a descriptive summary of various mitigation structures and is based on information provided by Jackson 1996, 1999; Forman et al. 2003; and the USFS website - Wildlife Crossings Toolkit (http://www.wildlifecrossings.info/beta2.htm). Not all of these passages may be designed specifically for amphibian and reptile use, but may have the potential to mitigate effects on these taxa.

Table 1. Descriptions of commonly used types of mitigation structures. Structures that are expanded on in the following text sections are denoted with an asterisk. Photographs of various structures and modifications to design may be viewed at the Infa Eco Network Europe (IENE) website (http://iene.instnat.be/photoalbum.html) and the Federal Highway Department website (http://www.fhwa.dot.gov).

Small Passages Beneath the Road Surface (< 1.5 m diameter or height)	
Amphibian and Reptile Tunnels*	Passages designed specifically to facilitate seasonal migrations to and from breeding and/or nesting sites, and movements between upland and wetland habitats. These tunnels have various dimensions and designs.
Wildlife Culverts *or* Ecoculverts	Passages located over water channels designed for small to medium-sized vertebrates. These tunnels are up to 120 cm wide with raised ledges that run the full length of the structure. The ledges provide a dry path and may be inundated only briefly during heavy rain.
Wildlife Pipes *or* Ecopipes	Dry passages of circular circumference designed to facilitate overland movements of small to medium-sized mammals. Originally installed for badgers in The Netherlands.
Drainage Culverts*	Culverts originally engineered for water passage and drainage modified to encourage wildlife passage. For example, shelves or floating docks may be installed, or water may be channeled through a trench within the culvert.
Large Passages Beneath the Road Surface (> 1.5 m diameter or height)	
Wildlife Underpasses: Culverts*	Conduits with embanked perimeters designed for a wide variety of species that may or may not allow for water passage. Variation of design include: circular or elliptical, concrete box, and open-bottom. Construction materials range from concrete to metal to wood. The spans of these passages are shorter than bridges, with entrance diameters of approximately 2 m.
Wildlife Underpasses: Expanded Bridges*	Where railways and highways cross over rivers and streams, expanded bridges provide both upland travel corridors adjacent to the waterway and stream corridors for riverine species. Open span bridges rest on abutments (located on both sides of the crossing), while multiple span bridges have intermediate support columns across their length in addition to abutments.
Viaducts	Larger than bridges, viaducts are elevated roadways used to span entire valleys that may extend over distances greater than 100 m providing unrestricted passages for a variety of species.
Ecotunnel	Expanded tunnel that is drilled through the earth allowing for wildlife passage below the road surface.
Large Passages Over the Road Surface	
Wildlife Overpasses *or* Ecoducts*	A structure that allows for wildlife to cross above a roadway. Designed primarily for large mammals, most range from 30 to 50 m wide, but may expand greater than 200 m. The term green bridge refers to an overpass with a continuous strip of natural vegetation across its length.
Landscape connector	The roadway is drilled through the earth as a tunnel allowing for undisturbed habitat above the infrastructure that facilitates wildlife passage.
Barriers and Guiding Components	
Fencing and Walls*	Diversion structure designed to impede movement across roads and direct wildlife towards passages. Construction materials are widely varied and include wire, chain link, rail, plastic mesh or concrete.

Amphibian and Reptile Tunnels

The installation of fauna tunnels between upland habitat and wetland breeding areas, or between isolated wetlands allows for the coexistence of amphibian and reptile migration and road traffic and is especially important for those species that do not access water corridors for travel routes. Tunneling systems are widely used in Europe and have more recently been employed in Canada and the United States in California, Florida, Massachusetts, Ohio, and Texas. A permanent tunnel system should allow for migration of adult amphibians from breeding grounds, migrations of adult returning to upland habitat, and the emigration of metamorphs from the breeding ponds (Podloucky 1989). Similarly, tunnels designed for reptiles should be placed along migratory routes to maximize encounter rates. An individual tunnel may be designed to allow for bi-directional movement of animals, or placed adjacent to another tunnel to be used in one direction only, often with a compulsory funneling device at the entrance to direct flow of animals entering the passage. A checklist for safe amphibian passages compiled by Eriksson et al. (2000) suggests that if several tunnels are needed they should be at most 30 meters apart. The closer the tunnels are to the breeding pond, the more accepted they are by amphibians. Brehm (1989) recommends that for amphibians that migrate between upland and wetland habitats, tunnels should be built in the direction of movement; this means the tunnel may cross the road at an angle. Dexel (1989) cautions that vertical entry shafts to tunnels are not suitable due to high mortality rates observed for amphibians. Waterpools near the culvert entrance can help serve as springboards for amphibians crossing roads (Eriksson et al. 2000), however, in Florida such pools attracted alligators potentially subjecting crossing animals to an increased predation risk, even though such an event was not observed during the study (Dodd et al. 2004).

Additionally, microhabitat conditions of the crossing structure may influence effectiveness. Olfaction plays a primary role during location of breeding habitat for certain amphibian species (Oldham 1967; Duellman and Trueb 1986), and research needs to be conducted to determine how olfactory cues may be affected within passageways. If environmental conditions change overnight (e.g., colder temperatures), amphibians migrating through tunnels may seek shelter or turn back. If animals were caught in the middle of a long tunnel, lack of appropriate shelter may result in mortality. Research is needed to determine whether minimizing the width of the highway, and therefore the length of the tunnel, or using shorter tunnels with intermediate median strips would be more effective in reducing the risk of such mortality (Jackson 1996). Ambient light penetration into fauna tunnels plays an important role in orientation during migration and lack of it may result in hesitation of species to enter the tunnel or cause them to try and climb back out of the entrance. Total duration of crossing time through tunnels was reduced when artificial lighting was available for spotted salamanders (*Ambystoma maculatum*) in Massachusetts (Jackson 1996). Using larger tunnels accompanied by grates built into the road surface may maximize ambient light. These grates are additionally important in providing aeration and equilibrium of temperature and moisture conditions within the tunnel potentially important for both amphibians (Brehm 1989) and snakes (CARCET website – project discussed in case studies section of this document). Furthermore, certain species of salamanders and snakes follow scent trails in order to locate breeding sites or migration routes, and it is therefore suggested by several studies that structure design allows for a layer of detritus and leafy substrate to remain undisturbed along the length of the passage (Wildlife toolkit website). The effectiveness of this measure in facilitating passage use has, however, not been tested. Water flow may potentially wash out substrate and scent trails, so culverts should be placed so as to not carry runoff. Slotted or grated culverts may not be appropriate for roads that require additional resurfacing.

Drainage Culverts

Drainage culverts originally designed to convey water under roads either explicitly or intermittently can be modified to provide fauna passages. Although many amphibian species use flowing water as a conduit, the installation of shelving or floating docks within culverts provides dry areas to reduce the risk of drowning, and is especially important for terrestrial reptiles. Another effective modification is to channel the water through the culvert, thereby providing an extended bank area (Jackson 1999). The potential for these structures to be adapted for wildlife use is often overlooked (Forman et al. 2003); yet such non-wildlife-engineered passages can provide important linkages across landscapes for various species (Rodriguez et al. 1996).

Wildlife Underpasses: Culverts

These passages are typically designed to serve multiple species and to generally improve landscape connectivity. Some culvert systems are installed to serve as a larger form of amphibian and reptile tunnels, and if so, many of the suggestions listed concerning such tunnels, may apply to these structures as well. Often, these terms are used interchangeably to describe structures, but in this document we emphasize that there is size difference, and that culverts may be designed for both wildlife and water passage. Underpass design, including dimensions, habitat type, and exclusion fencing are likely to affect fauna use (Norman et al. 1998). Underpass width and amount of extended banking increase the frequency of use by a wider variety of species (Veenbaas and Brandjes 1999). Screens in the form of trees or bushes should be planted to obscure the view of the road and can be combined with vegetation used for guidance and protection of smaller fauna (Eriksson et al. 2000). A diverse range of habitat types is likely to increase the number of species that may potentially make use of an underpass (Norman et al. 1998). Wildlife underpasses with open median designs are less confining and may provide intermediate habitat for amphibians and reptiles (Jackson 1999).

Where culverts serve as underpasses for streams and small rivers, oversize culverts, large enough to provide a corridor for wildlife passage may be used. Retaining or replicating natural streambed configuration within these culverts may appeal to animals that use streams as migration corridors (Jackson 1996; Eriksson et al. 2000). Open bottom culverts are therefore preferred, but if pipe or box culverts are used, the bottom should lie beneath the streambed ideally with the natural width of the stream course preserved. Substrate within the passageway should be similar to that of the natural environment. Adequate forms of cover should be available to provide a resting spot during migration in case of cool temperature or long travel time. Designs in Europe include the construction of benches along the sides of the culvert to provide dry passage during high water flow and to prevent drowning (Jackson 1999, Infra Eco Network Europe 2001). The desired shape of the fauna ledge walkways for the animals utilizing such provisions is being investigated (Brandges and G. Veenbaas, pers. comm.).

Wildlife Underpasses: Expanded Bridges and Viaducts

Where highways and railways cross rivers and streams, expanded bridges and viaducts can provide banking beneath the structure which allows species to travel adjacent to the water (Jackson 1999). These structures are designed mainly for larger fauna, and the degree to which amphibians and reptiles use them has not been adequately studied. In fact, the conditions under these passages may be too dry for amphibians use (Jackson 1999). These structures are more expensive to construct and maintain than culverts but may be generally more effective by preserving a greater width of natural habitat and being more open.

In 1993, Texas DOT proposed to construct a new bridge across the Colorado River. Concern that this project would affect the federally-listed Concho water snake (*Nerodia paucimaculata*) resulted in mitigation measures in the form of design adaptations (Jenkins 1996). We include this example to demonstrate that agencies need to consider the impact that road projects may have on surrounding wildlife and make adjustments when needed. Measures taken concerning this project included: 1) the bridge abutments were placed on top of a bluff area to maintain the integrity of bank areas used by snakes for basking and shelter sites, and no construction equipment was permitted on the bank; 2) to ensure that bank areas would not be inundated, all run-off was diverted into a basin located on the west end of the bridge; 3) structures installed during construction to control erosion remained in place until native vegetation was regenerated.

Overpasses

Wildlife overpasses or "natural" ecoducts have been constructed in Europe and are designed to join landscape elements on either side of the road by channeling traffic below the ecoduct (Bekker 1998). A variety of larger fauna use these passages, but the degree of amphibian and reptile use is still unclear. Primary advantages of these structures include that they are less confining than other types and allow for the maintenance of ambient conditions and natural vegetation (Jackson 1999). In addition to functioning as a passageway over roads, these structures may provide intermediate habitat for a variety of species (Jackson 1999). For example, several overpass projects in the Netherlands include the construction of wetlands to enhance the habitat value to amphibians (Bekker et al. 1995).

Barriers and Guiding Components

Fencing or walls can be installed to serve as a guiding system to passage openings. The barrier edge should not interfere with accessibility to the passage entrance, and the structure should be designed to prevent climbing, provide shelter and shade, and funnel wildlife toward crossing structures. Brehm (1989) determined that funnel-shaped drift fences or "swallowtail" barriers assisted amphibians in finding culvert openings. In addition, a drift fence height of 0.4

m with the upper edge bent, deterred amphibians from climbing as well as enabled individuals located on roads to cross over easily, thereby gaining access to the culvert. This overhanging lip design has reduced trespass onto the road by reptile species as well (Dodd et al. 2004). Joints between fencing and the tunnel entrance should be sealed and smoothed to prevent injury to animals utilizing the crossing and to prevent vegetation from growing which would enable animals to climb up onto the road (Eriksson et al. 2000). An overhanging lip on concrete guiding structures effectively prevents climbing and protects animals from overhead predation (Eriksson et al. 2000; U.S. DOT 2001). Research suggests that tunnel and fencing systems should be as natural as possible and placed in a manner appropriate to the surroundings and the needs of the target animals (Vos and Chardon 1994). Structures should be constructed of durable materials to minimize maintenance; smooth concrete has been found to work well (Eriksson et al. 2000, Smith and Dodd 2004). Guide fences should be adapted to the direction of migration route, and of sufficient length to prevent animals from simply entering the highway upon reaching the barrier end. Aresco (2003) found that extending fence ends out perpendicularly for several hundred meters prevented turtles from accessing the highway.

Comparison of Structure Efficacy

All of the passage types discussed above vary in their entrance dimensions, construction materials, and the habitats in which they are effective. Opening types range from open bottom arches, box culverts and circular pipes, to structures with less confined dimensions such as overpasses. Multiple studies have revealed that a broader range of species are likely to use passages when openings are greater than one meter in diameter (Brehm 1989; Dexel 1989; Yanes et al. 1995; Jackson 1999; Eriksson et al. 2000). Although generally more expensive, viaducts and large overpasses may be preferred to culverts because they provide greater connectivity and degree of openness while maintaining natural features, thereby accommodating more species (Jackson 1999). However, we caution that agencies should not rely on the installation of one large passage at one location as a means to mitigate the effects of roads on all wildlife groups. Research indicates that species preferences related to passage types and habitat placement are varied (Little et al. 2002). In other words, designing solutions to transportation-based conflicts with wildlife proves to be complicated, and requires that future experiments be conducted to evaluate responses of species to various passage features. Relative to mammals, there are few studies that evaluate factors affecting passage use by amphibians, and even fewer that focus on reptiles.

To date, evaluations of faunal crossings have revealed that multiple variables can impact efficacy concerning amphibians and reptiles, including: type and dimensions (total length, width and height) of structure (Jackson 1999), degree of openness within structure (Brehm 1989; Dexel 1989; Yanes et al. 1995; Rodriquez et al. 1996), placement in reference to traditional migration routes (Brehm 1989; Podloucky 1989; Rodriguez et al. 1996; Roof and Wooding 1996; Rosell et al. 1997), substrate and construction material type (Yanes et al. 1995; Jackson 1996; Eriksson et al. 2000), vegetative cover (Rodriguez et al. 1996), noise (Langton 1989), moisture (Brehm 1989; Jackson 1996), temperature (Langton 1989), hydrology (Jackson and Tyning 1989; Rosell et al. 1997; Eriksson et al. 2000),and amount of ambient light available (Jackson and Tyning 1989; Krikowski 1989; Beier and Loe 1992; Jackson 1996; Rodriguez et al. 1996). The impacts of these characteristics on the effectiveness of crossing structures are summarized in Table 2.

Table 2. Effects of various characteristics on the efficacy of road-crossing structures.

Structure Characteristics	Effect	Taxonomic Groups Tested	References
Type of opening	Open-bottom arches and box culverts are preferred designs to maintain natural substrates. In one study, reptiles crossed more frequently through circular openings, while amphibians preferred square.	Amphibians Reptiles	Jackson 1999 Rosell et al. 1999
Dimensions; openness within structure	Two-directional tunnels with large cross-sections represent a most suitable solution. Amphibians accepted a tunnel of 0.2 m in diameter and 0.4 m in total height. A greater proportion of toads used large tunnels (diameter 1 m; length 15mm). Snakes and lizards demonstrated a higher crossing rate in culverts and underpasses 2 m wide.	Amphibians: crested newt, smooth newt, spadefoot, common toad, common frog, moor frog, edible frog Reptiles: lizard and snake	Brehm 1989 Dexel 1989 Yanes et al. 1995 Rodriguez et al. 1996
Placement	The axis of the passage should be aligned towards breeding areas with placement in reference to traditional routes. Proximity of passages to breeding habitat is important. Structure usage is determined by location with respect to habitat.	Amphibians: crested newt, smooth newt, spadefoot, common toad, common frog, moor frog, edible frog Reptiles: lizard and snake	Brehm 1989 Podloucky 1989 Rodriguez et al. 1996 Roof and Wooding 1996
Substrate	Retaining or replicating natural stream conditions within culverts may increase use by animals that use streams as migration corridors. Appropriate substrate (flat rocks) needs to be provided for cover. Use of dry substrate should be avoided.	Amphibians	Yanes et al. 1995 Jackson 1996 Eriksson et al. 2000
Construction material	Design and materials should be durable, requiring minimal maintenance; smooth concrete works well.	Amphibians	Eriksson et al. 2000
Vegetative cover	The presence of vegetative cover surrounding a passage entrance was favored.	Reptiles: lizards and snake	Rodriguez et al. 1996
Noise	Vehicular noise may cause amphibians to hesitate, but does not substantially interrupt migration.	Amphibians: frogs and toads	Langton 1989
Moisture	Effects of moisture on olfactory cues within passages need to be investigated. Maintenance of damp conditions within tunnels, via slots or grates is important	Amphibians: salamanders, frogs	Brehm 1989 Jackson 1996
Temperature	Temperature disparities within small passages may cause hesitation. Larger underpasses and grating may increase airflow.	Amphibian species and snakes	Langton 1989 CARCET website
Ambient light	Maintenance of natural light via grates will assist in guiding animals through passages, and provides places to bask.	Amphibians: frogs, toads, salamanders Reptiles: snakes and lizards	Krikowski 1989 Beier and Loe 1992 Jackson 1996 Rodriguez et al. 1996
Hydrology	Design features at tunnel entrances should divert runoff to prevent flooding.	Amphibians: spotted salamanders Reptiles: snakes	Jackson and Tyning 1989 Rosell et al. 1997 Eriksson et al. 2000

Measuring the Effectiveness of Road-Crossing Structures

In the recent Road Ecology text, experts recommend that studies measure six criteria as a means to evaluate mitigation success in terms of the overall goals to reduce road mortality and barrier effects (Forman et al. 2003). These criteria include: (1) reduction of road-kill rates post-mitigation efforts; (2) maintenance of habitat connectivity; (3) persistence of gene flow among populations; (4) affirmation that biological requirements are met; (5) allowance for dispersal and recolonization; (6) maintenance of metapopulation processes and ecosystem function. This section summarizes case studies (organized by year) that attempt to address these criteria in assessment of various mitigation efforts. Several of these projects were published within peer-reviewed journals, or symposia proceedings, while others were discovered within on-line databases or websites.

Generally, evaluation studies focus on mammal passage and are not very rigorous by design. Most studies are strictly designed to evaluate efficacy in terms of comparing pre-versus post-construction measurements of road mortality and concentrate on one species. Few develop and test hypotheses, or list predetermined criteria that provide a basis from which to assess passage performance (Forman et al. 2003). Evaluations of passage effectiveness in terms of connecting landscapes and processes are often based solely on total count measurements of individuals observed crossing. However, Forman et al. (2003) emphasize that in order to evaluate the success of a passage based on the six criteria, studies need to place these numbers in a population context (abundance and distributions in the vicinity) across broad time scales (frequency of crossing).

Case Studies

(1) *Amphibian Tunnels in Amherst, Massachusetts (Jackson and Tyning 1989)*

In 1987, two tunnels (with slotted openings) and diversion fences were installed to facilitate the safe passage of spotted salamanders under a road to breeding sites.
This project focused attention on tunnel design and placement. The tunnels were constructed adjacent to over-wintering habitat in efforts to maximize accessibility, and minimize the amount of fencing needed to guide the animals; the diversion fences were designed to encompass the over-wintering area yet to not form a barrier preventing individuals from accessing the passage

openings. Mark-recapture efforts revealed that 68% of salamanders captured along the length of the diversion fence and 76% of those observed at the tunnel entrance successfully crossed under the road. The effectiveness of this project was therefore measured by the number of individuals that encountered a fence and passed through a tunnel. These passages were deemed successful in reducing road mortality of spotted salamanders and maintaining migration corridors. However, concern that the fences formed a barrier to the migratory movements of other species stemmed from the fact that surveyors encountered wood frogs (*Rana sylvatica*) along the length of the diversion fences yet observed few actually using the tunnels to cross the road.

(2) *Fencing and Underpasses along Alligator Alley (Foster and Humphrey 1995; Land and Lotz 1996)*

In efforts to minimize the impacts of upgrading State Road 84 (Alligator Alley) to Interstate 75 on Florida panthers (*Puma concolor*), 24 wildlife underpasses and fences were installed along a 64-km portion of the highway that intersected their range. Foster and Humphrey (1995) monitored four of these underpasses with game counters and cameras, and recorded 9 crossings by alligators among the wildlife using the passages. Land and Lotz surveyed these passages again in 1996, and although precise numbers are not reported, observed an approximate 50% increase in structure use by alligators. Although this project was designed to benefit Florida panthers, monitoring efforts recorded a variety of wildlife species using the underpasses.

(3) *Barrier Fencing and Culverts for Desert Tortoises (Boarman and Sazaki 1996; Boarman et al. 1998; Boarman, pers. comm.)*

Research indicates that desert tortoises, a threatened species, are particularly vulnerable to the full gamut of road effects. In 1990, the California Department of Transportation (Caltrans) installed a barrier fence (24 km long) along State Highway 58 to protect tortoise populations from the effects associated with widening the highway. In addition, 24 culverts and three bridges designed to convey runoff were installed, and eventually connected via funnels to the barrier fence in 1992. A partnership among numerous agencies developed a project to measure the effectiveness of this mitigation system in reducing road mortality of tortoises, facilitating movement across the highway, and the overall recovery of populations within the road-effect zone. This project used the following methods to address effectiveness: comparison of road-kill records from transects along sections of fenced and unfenced highway, placement of sand traps at culvert entrances, installation of an automated reading system (ARS) to assess culvert use by tortoises marked with Passive Integrated Transponder (PIT) tags (Gibbons and Andrews 2004), and completion of population surveys on a 1.9 km^2 plot every four years. Transects conducted along unfenced sections of highway in 1993, 1994, and 1996 revealed a total of 1078 road-killed vertebrates (24 species), of which desert tortoises comprised 3.2% (n=35), yielding a mean of 12.6 casualties per km. Over the same years, the total number of road-kills was 89% lower along fenced sections of highway, with a mean of 1.3 casualties per km, indicating a statistically significant reduction in road casualties. Furthermore, there were 93% fewer tortoise carcasses and 78% fewer shovel-nosed snake (*Chionactis occipitali*) casualties (which composed 3.6% of the total road-kills along unfenced sections). Of 172 PIT-tagged tortoises (all originally located within 3 km of the culverts), the ARS recorded 75 crossings through the culverts by five individual tortoises. In fact, one tortoise passed through the culvert 29 times over seven days. Sand traps revealed that several snakes and lizards also used the culverts to cross the road. Population surveys are ongoing, but transect data reveal that evidence of tortoise activity within 1.6 km of the highway is 30% greater along fenced sections.

(4) *Tunnels designed for red-sided garter snakes at Narcisse Wildlife Management Area (CARCET website)*

The Narcisse Wildlife Management Area (NWMA) is renowned internationally for its' large aggregations of snakes near den areas during spring and fall; in fact approximately 20,000 people visit the area annually to witness this unique phenomenon. There has been increasing concern about the populations' ability to sustain high levels of road mortality that primarily occurs during the fall migrations back to the dens. Road surveys conducted between 1991 and 1993 revealed that mortality levels approach 10,000 animals annually, despite the presence of an intact tunnel and fence system. Data were collected over three seasons by Joshua Chan (for thesis research) and staff at NWMA which provided evidence that fencing successfully directed snakes to passage entrances, and that some snakes used passages for travel, however, many individuals preferred to bask within the warm entrances rather than pass through. In 1994, staff expanded the drift fencing by 500 meters along the west side of the highway as a means to intercept a greater number of snakes during fall migrations back to the den area. The fencing guided snakes towards two new tunnels designed of polymer concrete with a slotted grate to test the response of individuals to the structures before installation. In addition to direct monitoring of the tunnels, snakes were captured, released near the openings, and then observed. Snakes readily entered and successfully traveled through the tunnels, suggesting that the grate produced conditions conducive to movement by allowing natural heat and light to enter the tunnels. Since 1995, the management area has added numerous modifications to mitigation efforts including: drift fence expansion to overlap with approximately half of the snakes' migration corridor, formation of a snake mortality advisory group, and installation of four additional passages (small pipes). Despite these efforts, road mortality of snakes during fall migrations remains sporadic with high pulses during certain years. As a result, the advisory group continues to evaluate problems and experiment with new techniques.

(5) *Tunnel for Western Toads in Davis, California (Wildlife Crossings Toolkit)*

In 1995, construction workers removed topsoil from a drainage pond for nearby highway improvement; the pond provided breeding habitat for western toads. Motivated by public concern, the Davis city council voted to install a tunnel (squash pipe) concurrent with the improvement projects to provide an outlet from the drainage pond. However, no biological evaluations were conducted regarding the site and function or placement of this culvert. No toads have been reported using the structure and no efforts to rigorously monitor effectiveness have been conducted since installation. This particular case demonstrates the importance of conducting assessments to establish the need for mitigation efforts, placement of structures, and establishing goals for a project.

(6) *Amphibian tunnel and fence designed for Houston toads (*Bufo houstonensis*) in Bastrop County, Texas (Jenkins 1996; Wildlife Crossings Toolkit)*

Biological surveys conducted to evaluate the potential impacts that proposed safety improvements would have on the threatened Houston toad revealed that the existing roadway posed a threat to this amphibian. Following the evaluation of different mitigation strategies, biologists opted to modify existing drainage culverts by adding short sections of diversion fencing designed to guide toads into the culverts. The fencing was actually formed by cutting steel culverts longitudinally to form arcs, and then buried 50 cm deep in the soil. The culverts themselves were not modified for amphibian use, and became impassable when flooded. The diversions were placed along known corridors used by the toads during seasonal movements. However, the entire 1830 m section of highway recognized by biologists as a high-risk area for the toads was largely left untreated. Post-construction monitoring by DOT indicated that no toads were crossing the road via the culverts, and that although the barriers effectively reduced road-kills in the vicinity of placement, aggregations of dead toads occurred at the barrier endpoints. Funding was not available to install specialized amphibian tunnels with slotted openings, or line the entire highway section with fencing as initially designed.

(7) *Mitigation measures for Hermann's tortoises (Guyot and Clobert 1997)*

In addition to the physical removal of individuals from the construction site of a new highway, the Highway Society of France installed barrier fencing, one tunnel, and two culverts to minimize road mortality and facilitate movement under the highway. These efforts were deemed successful through data collected four years following construction. Staff observed only five road-killed tortoises along the 4-km section of highway lined by fencing, and mark-recapture results indicated that tortoises used both tunnels and culverts to successfully cross the road and that the adult population was stable.

(8) *Amphibian tunnels in Albany County, New York (Wildlife Crossings Toolkit)*

Surveys conducted along County Road 202 revealed that amphibians frequently crossed the road and mortalities were extremely high, particularly along sections that fragmented wetland habitat. To provide safe passage for these animals, two concrete tunnels with box openings and barrier walls (constructed of wood) were installed in 1999. The mitigation structures were designed based on recommendations published by Jackson (1996, 1999) with some minor modifications. The width and height of the tunnels were 1.2 m in efforts to provide passage for a wider range of species and allow room for the natural substrate placed along the bottom. The installation of these structures was linked to highway improvement, thereby reducing construction costs. Surveys continued in monitoring the project site and have reported a 90% decrease in road mortality, and observed 8 of the 20 known amphibian species using the tunnels.

(9) *Slotted Culvert for Timber Rattlesnakes in Shawnee National Forest (Wildlife Crossings Toolkit)*

The Shawnee National Forest planned to resurface a road that timber rattlesnakes crossed during seasonal migrations between limestone bluffs and wetland areas. There was concern that the increased traffic speed and volume associated with paved surfaces, and the expected increased use of the surface by snakes for thermoregulation would intensify road mortality. This concern facilitated the installation of three slotted culverts and cloth fencing to minimize the impacts of this road on mortality and movement. Fencing was folded and buried to 6 inches deep to prevent trespass below, and extended 2.5 feet above ground to prevent trespass above. The slotting allowed for ambient light and moisture to be retained within the culvert, and leaves were placed along the bottom to provide appropriate substrate. Monitoring efforts recorded the passage of two timber rattlesnakes in the two years following installation. Researchers hope that over time more snakes will incorporate the passages into their migration routes, and emphasize that an increased number of pre-construction surveys, particularly during seasonal migrations, would have helped guide the placement of structures.

(10) *Barrier-Wall Culvert Project at Paynes Prairie (Dodd et al. 2004)*

In 2001, Florida DOT constructed an Ecopassage across Paynes Prairie in efforts to minimize highway impacts on surrounding wildlife. This project entailed the installation of a concrete wall with an overhanging lip interconnected to eight concrete culverts. The wall extends for 2.8 km across the prairie basin along the east side of the highway, and for 2.5 km along the west side. This project added four cylindrical tunnels designed to convey both water and wildlife in addition to the four preexisting box culverts. Excluding birds and hylid treefrogs, surveyors observed 2411 road-killed vertebrates over the twelve months prior to construction. Following installation, road mortality was reduced by 93.5%; only 158 vertebrates were observed. Including hylid treefrogs, which accounted for 69% of the total road-kills, the Ecopassage reduced the overall vertebrate mortality by 65%. The overall number of road-killed treefrogs actually increased following construction, because they easily trespassed the concrete barrier. However, the number of road-killed snakes, turtles, ranid frogs, and alligators considerably declined. This project also effectively reduced the mean number of vertebrates road-killed over a 24-hour period from 13.5 to 4.9. Approximately 73% of the road casualties (excluding hylids) were concentrated along a 400 m section of the prairie rim located beyond the extent of the barrier. Through monitoring, scientists detected an increase in culvert use; 51 species of vertebrates used the eight passages, compared to the 28 detected pre-construction, and capture success (in screen traps) within the passages increased 10-fold. This project was deemed successful in that data indicate five of the six criteria summarized by Forman et al. (2003) were met.

Problems

Although prospects for mitigation seem attainable, there remain logistical problems with several aspects of design. Overhanging vegetation may facilitate the trespass of animals over a concrete barrier, and consequently requires regular maintenance (Ryser and Grossenbacher 1989; Dodd et al. 2004). Some species may be capable of climbing vinyl fencing, without the aid of vegetation (Aresco 2003). Furthermore, passage entrances and guiding systems need to be kept clear of thick vegetation that may block access (Wildlife Crossing Toolkit – Houston toad case study) or deter movement (Ryser and Grossenbacher 1989; Eriksson 2000). Gaps may develop along the base of fences as a result of erosion, washouts, digging mammals, or vandalism, and may subsequently allow animals access to the highway that oftentimes results in road mortality (Boarman, pers. comm.; Roof and Wooding 1996; Houston toad case study). Additionally, fences with large mesh sizes may permit smaller animals to slip through (Guyot and Clobert 1997). Solid material may therefore be preferred for barrier construction. Finally, over time, a heavy build-up of silt in culverts and tunnels decreases the openness of a passage and may need to be periodically removed (Dodd et al. 2004).

Another potential problem is that passages create aggregations of animals that occur along predictable routes. Several studies have expressed concern that such densities may increase predation or collection risk, negating any beneficial effects in regards to road mitigation. Little et al. (2002) conducted a literature review to evaluate the potential for predators to exploit passages during hunting forays, and to determine if prey species actively avoid passages frequented by predators. Based on the limited number of observational studies, predators are known to opportunistically forage in or near passages, but there is no evidence to suggest that this predation has caused the decline of any prey species. However, the authors discovered one confirmed report from Australia of tunnels increasing predation risk of mountain pygmy possums (*Burramys parvus*) (Mansergh and Scotts 1989). Additionally, Aresco (2003) reported the mortality of 92 turtles as a result of predation along the barrier fence at Lake Jackson, and suggested that such mortality could be reduced if more culverts were installed along the length of the fence to enable faster migration. The review by Little et al. (2002) discovered observational evidence suggesting that prey species avoid using passages frequented by predators familiar to them, or they may alter their activity periods to use passages at a different time than predators. The authors emphasize that there is a need for research to test hypotheses concerning these questions within both population and ecological contexts. Several studies suggest that human access to passage entrances and along barriers needs to be restricted in efforts to limit collection, disturbance, and eliminate safety concerns (Aresco 2003; Dodd et al. 2004). Some agencies may even be reluctant to advertise the location and purpose of structures in efforts to protect animals from illegal collection (S. Ballard, pers. comm.).

Recommendations

- Conduct more research on the effects that roads and vehicles have on inhibiting road crossing by amphibians and reptiles in terms of indirect effects.
- Study the consequences of roads and traffic on amphibian and reptile *populations* (cf. road mortality). These studies should be conducted at broad spatial and temporal scales in attempts to realize the full effects that roads exert on amphibians and reptiles. Field studies should be conducted at local areas and multi-site areas over periods spanning a minimum of one-generation of target species to account for migration patterns and the natural variance of the populations in question.
- Acquire and incorporate information on the location and importance of chronic road-kill sites to improve placement of road crossing structures. The feasibility of using GIS and spatial modeling to identify key habitat features that serve as corridors to amphibian and reptile movements should be investigated.
- Conduct field experiments and monitoring studies that are hypothesis driven to evaluate the efficacy of road crossing structures and determine maintenance requirements. The following techniques may be employed:
    - Mark-recapture studies
    - Radio tracking individuals
    - Counters

  - Cameras (Infrared)
  - Track beds

- Establishment of performance standards for structures based on characteristics and needs of wildlife.
- Combination of radio-telemetry and population censuses to determine what percentage of individuals use passages to cross roads. In many studies, culvert use seems low, although mortality is reduced. Are these efforts simply fragmenting populations?
- Develop ways to communicate this information effectively and efficiently to all interested parties and provide means for feedback. This should be viewed as an ongoing, iterative process.
- Applications of this information to planning, conservation, management, design, and policy need to be considered for effective mitigation of road effects on amphibians and reptiles.

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