Research to Inform Caltrans Best Management Practices for Reptile and Amphibian Road Crossings

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Chapter 1. Executive Summary

Introduction

In October of 2014, the U.S. Geological Survey (USGS) began a 5-year project to conduct research to inform Best Management Practices (BMPs) for amphibian and reptile crossing and barrier systems in California. To inform future conservation and transportation planning, this project involved identification of species at highest risk of negative road impacts, creation of geodatabase and spatial mapping tools that crosswalk with California Essential Habitat Connectivity Planning, and field research to address information gaps in the efficacy of reptile and amphibian passage and barrier systems.

Per the agreement with California Department of Transportation (Caltrans; agreement 65A0553), this project was part of a broader collaborative effort between the Western Transportation Institute (WTI) of Montana State University and USGS Western Ecological Research Center (WERC). As part of this broader project, WTI conducted a worldwide literature review and gap analysis and produced a BMP manual for herpetofauna in California (Langton and Clevenger 2021). WTI and USGS were contracted separately although we worked closely together throughout this broader effort and each brought particular expertise to the project. WTI has expertise in highways, the attributes of the highway environment, and broad international experience with road ecology and herpetofauna connectivity systems worldwide. USGS WERC has expertise with California amphibian and reptile species and their ecology, study design and implementation, and landscape connectivity and road ecology.

Overall Program Objectives and Tasks

To meet the objectives in the contract, the project was composed of six major tasks:

1) Meet with Caltrans and other California herpetologists to establish collaborative networks with California herpetologists and inform them about the Caltrans amphibian and reptile highway crossing design project.

2) Perform a risk analysis based on an evaluation of California amphibian and reptile species ranges, life histories, population locations, habitat needs, and movement patterns to identify road sensitive species and/or confirm road sensitive species previously identified by Caltrans.

3) Create spatial data and maps to crosswalk with the California Essential Connectivity Map (Caltrans/California Department of Fish and Wildlife (CDFW) / U.S. Department of Transportation (DOT)) and Amphibian and Reptile Species of Special Concern Maps (CDFW) for species evaluated in Task 2 and identify primary roadways that transect habitats for these sensitive species. This was done in consultation with the WTI research team, Caltrans, wildlife agencies (U.S. Fish and Wildlife Service (USFWS) and CDFW) and species experts.

4) Assist WTI in the synthesis of the state of the practice in reptile and amphibian highway crossings by compiling and reviewing literature on amphibians and reptiles and mitigation measures to reduce road impacts, including identifying research gaps and future research needs.

5) Using expertise from within WERC and input on roadways and animal crossings from WTI, develop and design a plan for field research to evaluate key design and environmental attributes of functional passage structures for select amphibian and reptile species. Select sensitive amphibian and reptile species from the prioritized list developed in Task 2. Conduct field studies at existing (and new if possible) crossing structures to determine effective means for enhancing the ability of the selected species to cross highways. Give preference to multiple replicated sites that allow for simple experimental manipulations.

6) Provide expertise on California amphibians and reptiles to the WTI research team for the preparation of the Best Management Practices (BMPs) manual. Prepare report of Tasks 1-5 and a manuscript for presentation and/or publication.

Establishing Collaborative Networks (Task 1)

We began the first task by holding a special session at the California-Nevada Amphibian Populations Task Force (APTF) in Calabasas, CA on January 8-10, 2015. The session was entitled "Amphibian (and Amphibious Reptile) Road Ecology" and hosted by USGS with guest speakers Tony Clevenger (WTI), Tom Langton (Herpetofauna C I Ltd), Sally Brown (USFWS), Michael Westphal (U.S. Bureau of Land Management), Michael Hobbs (San Jose State University) and Chris Brown (USGS). We used this venue to highlight the project and to begin collaborative networking. Collaborations continued throughout the contract period through many meetings and communications with WTI, California scientists and herpetologists, Caltrans state and district biologists, USFWS, CDFW, U.S. Forest Service (USFS), and other scientists and herpetologists throughout the state. We also attended and presented at multiple conferences and meetings such as the Desert Tortoise Council Symposium (2016), annual APTF meetings (2015-16, 2018-2019), Western Section of the Wildlife Society (2019), USGS Amphibian Research Monitoring Initiative (ARMI 2015-2019), and the International Conference of Ecology and Transportation (2015, 2019).

Tasks 2 through 5 are individually summarized in the following subsections of Chapter 1 of this report along with summaries of findings, relevance of findings to informing the BMPs, and suggestions for future studies. Individual comprehensive reports for the risk analysis (task 2), geodatabase (task 3), and field research (task 5) are presented in subsequent Chapters.

Risk Assessment (Task 2)

Caltrans considers the need for barrier structures and safe wildlife road-crossings important to maintain the long-term viability of wildlife populations (Caltrans 2019). To prioritize these efforts for herpetofauna, we identified species that are most at risk of extirpation from road-related impacts. With over 160 California species and a lack of species-specific research data, we developed an objective risk assessment method based upon road ecology science. Risk scores were based upon a suite of life history, movement, and space-use characteristics associated with negative road effects that were applied in a hierarchical manner from individuals to species (Figure 1). Considerations included movement distances, movement frequency, speed, habitat preferences, movement behavior (territorial, non-territorial, vs. migratory), fecundity, range size and conservation status. All California herpetofauna species (and some subspecies) were ranked into five relative categories of road-related risk to both aquatic and terrestrial connectivity (very-high to very-low) based upon 20% increments of all species scores.

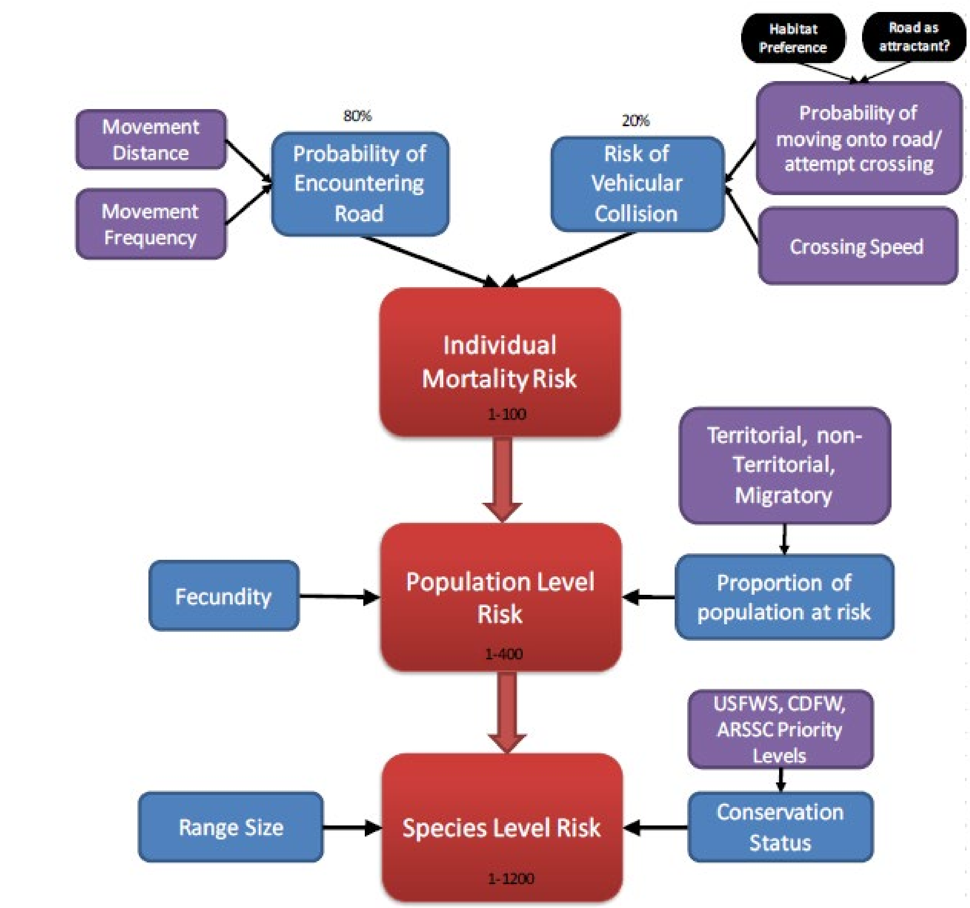

Figure 1. California Reptile and Amphibian Road Risk Assessment Conceptual Model.

All chelonids, 72% of snakes, 50% of anurans, 18% of lizards and 17% of salamander species in California were ranked at high or very-high risk from negative road impacts. Results were largely consistent with local and global scientific literature in identifying high risk species and groups.

Overall, snakes and chelonids had the largest proportion of species at high risk for negative road impacts due to longer movement distances (home range and/or migratory), lack of road avoidance, and relatively low fecundity in comparison to other herpetofaunal groups. This includes the desert tortoise, that has been shown to suffer from high road mortality negatively affecting population abundance in the Mojave Desert, and pond turtles, that travel kilometers within perennial waters and intermittent aquatic habitats to forage and find mates. In addition, female pond turtles migrate from their aquatic habitat to terrestrial habitats to nest and lay eggs, which make roads that parallel aquatic habitat a threat to both females and hatchlings.

Many large colubrid snakes and rattlesnakes ranked high. They are not only attracted to paved road surfaces for thermoregulation but have wide home ranges or move large distances between winter hibernacula and summer foraging areas. Long foraging movements within aquatic habitats also contributed to many garter snakes falling within the highest road risk categories.

Approximately half of California anuran species were ranked at high risk of negative road effects. These include Bufonid toads and red-legged frogs that may move large distances in both aquatic and terrestrial habitats to satisfy their annual resource requirements. Newts and several Ambystomid salamander species whose populations annually migrate between aquatic and upland habitats also ranked as high risk. Only a few wide-ranging lizard species scored in the highest risk categories including the Gila monster, leopard lizards, and two horned lizard species.

This risk assessment approach compared the susceptibility of species to negative road impacts. Commonly, there are numerous populations that occupy areas with greatly differing road pressures within a single species range. The actual risk to specific populations will depend upon local road densities, road types, traffic, and road locations in relation to species habitat and movement corridors. Therefore, it will be important to reassess the risk of roads to specific populations and to evaluate and compare alternatives at the local scale.

To help inform transportation planning and for evaluating the suitability of different best management practices, the risk of roads to both terrestrial and aquatic connectivity was assessed. Thus, semi-aquatic species have two risk scores. Some scored high in both habitats, while others scored high in only one. This is important when evaluating the need for underpasses and other terrestrial crossings versus bridges and fish passages. For example, underpasses, barriers and other structures may be suitable for species with high terrestrial risk scores; such as tortoises, colubrid snakes, rattlesnakes, and Ambystomid salamanders. Conversely, the use of fish passages and bridges could also be considered for species with high aquatic risk scores; such as the giant gartersnake, California red-sided gartersnake, two-striped gartersnake, and Sonoran mud turtle. Both terrestrial and aquatic passages may be needed for species groups that ranked high in both categories; such as pond turtles, Bufonid toads, newts and red-legged frogs. Along with this, buffer distances for terrestrial and aquatic habitats were calculated to encompass 95% of population level movements of all species. This provides information to agencies deciding whether a population is close enough to a road (within buffer distance) to warrant mitigation, the need for a barrier, and whether a goal should be to provide population-level connectivity or allow for occasional dispersal to provide long-term genetic connectivity.

A simplified list of high and very-high risk species is provided in Table 1. This work has been published (Brehme et al. 2018). The journal article with all California species rankings and buffer distances is included as Chapter 2 and is available at *https://link.springer.com/article/10.1007/s10980-018-0640-1*.

Table 1. California Amphibians and Reptiles Ranked at High and Very-high Risk of Negative Road-related Impacts.

GROUP	VERY-HIGH RISK	HIGH RISK
Terrestrial Snakes	Alameda Striped Racer Baja California Coachwhip Baja California Ratsnake California Glossy Snake Coachwhip Coast Patch-nosed Snake North American Racer Panamint Rattlesnake San Joaquin Coachwhip Striped Racer	California Lyresnake Desert Nightsnake Mojave Rattlesnake Nightsnake Red Diamond Rattlesnake Regal Ring-necked Snake Sidewinder Sonoran Lyresnake Speckled Rattlesnake Spotted Leaf-nosed Snake Western Groundsnake Western Diamond-backed Rattlesnake Western Patch-nosed Snake Western Shovel-nosed Snake Western Rattlesnake
Aquatic Snakes	California Red-sided Gartersnake Giant Gartersnake San Francisco Gartersnake Two-striped Gartersnake	Aquatic Gartersnake Common Gartersnake Northwestern Gartersnake Sierra Gartersnake Western Terrestrial Gartersnake
Freshwater Turtles	Northern Western Pond Turtle Southern Western Pond Turtle Sonora Mud Turtle	
Tortoises	Mohave Desert Tortoise	
Toads	Arroyo Toad Black Toad Sonoran Desert Toad Yosemite Toad	Great Plains Toad Western Spadefoot Woodhouse's Toad
Frogs	California Red-legged Frog	Cascades Frog Northern Red-legged Frog Oregon Spotted Frog
Lizards	Banded Gila Monster Blunt-nosed Leopard Lizard Cope's Leopard Lizard Desert Horned Lizard Flat-tailed Horned Lizard	Long-nosed Leopard Lizard San Diegan Tiger Whiptail Switak's Banded Gecko
Salamanders	California Newt Callifornia Tiger Salamander Red-bellied Newt Sierra Newt	California Giant Salamander Rough-skinned Newt Santa-Cruz Long-toed Salamander Southern Long-toed Salamander

Spatial Mapping (Task 3)

Caltrans and CDFW commissioned the California Essential Habitat Connectivity (CEHC) Project because they consider a functional network of connected wildlands essential to the continued support of California's diverse natural communities in the face of human development and climate change (Spencer et al. 2010). CEHC maps and spatial layers depict large, relatively natural habitat blocks greater than 809 ha (2000 acres) that support native biodiversity and areas deemed essential for regional scale animal and plant connectivity. These maps were intended to make transportation and land-use planning more efficient and less costly, while helping to reduce wildlife-vehicle collisions. They are available on the CDFW Biogeographic Information and Observation System (BIOS) website *https://wildlife.ca.gov/Data/BIOS*.

Essential Connectivity Areas (ECA), Natural Landscape Blocks (NLB), and Natural Areas_small (NA) from the Essential Connectivity Map geodatabase were provided by CDFW. Although habitat blocks greater than 809 ha are appropriate for planning connectivity for large mammals, small animals can persist on smaller size patches. Therefore, we merged ECA, NLB, and NA areas 10 ha or greater. The resulting layer was then dissolved into a single polygon feature class with a buffer of 100 meters added to it. This connected many of the smaller polygons and better represented natural areas large enough to support sensitive amphibian and reptile populations. We then prepared a spatial geodatabase that intersects the modified CEHC map, State Highways and high-risk species ranges from the California amphibian and reptile road risk assessment (Brehme et al. 2018). This geodatabase was designed to be a useful planning tool for Caltrans to quickly identify road segments which may warrant planning for increased connectivity of high-risk amphibian and reptile species.

The spatial geodatabase (CalTrans_SpeciesRoadRisk_Map.mpk) includes:

1) CEHC lands merged with smaller habitat blocks (>10 ha).
2) Ranges of high and very-high risk amphibian and reptile species.
3) California highway segments that intersect habitat ranges of high and very-high risk amphibian and reptile species.
3) California highway segments that intersect habitat ranges of high and very-high risk amphibian and reptile species and CEHC lands.
4) The total number of high and very-high risk species habitat ranges that intersect the highway segments and CEHC lands.

Here we show an example of a high-risk species density map for the state (Figure 2) and an individual species map (Figure 3), where the species habitat range intersects CEHC lands and state highway systems. Note that the accuracy of each species road risk map is dependent upon the accuracy of its most recent range map, which varies by species (see Chapter 3 for sources). Because many species are patchily distributed throughout their ranges, species may not be occupying habitat along all intersecting highway segments. Therefore, highlighted road segments indicate the possibility of species occupancy as well as known occupancy.

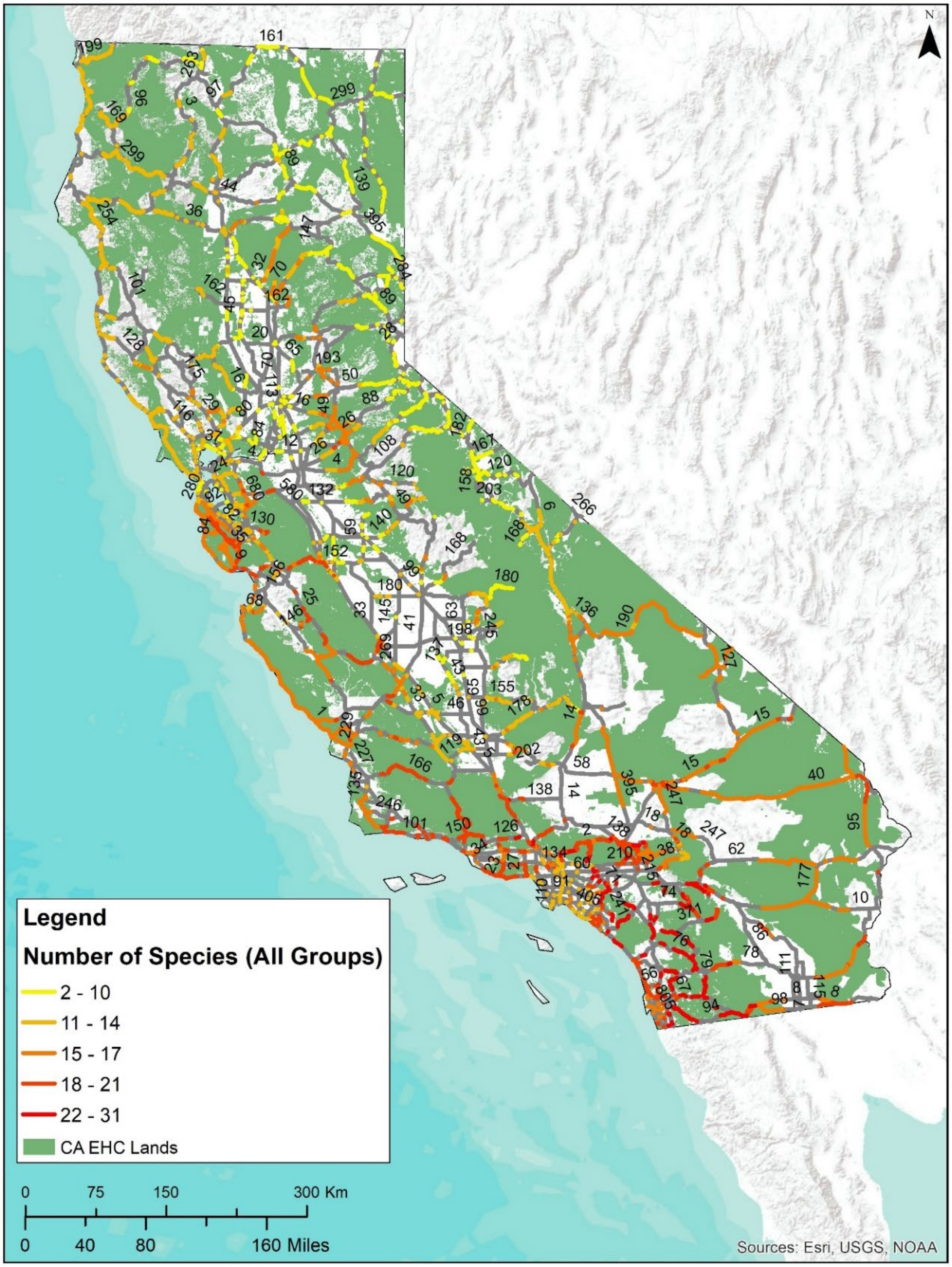

Figure 2. Density of High and Very-High Risk Reptile and Amphibian Species across the State Highway System (Elise Watson, USGS). Note: California Highway Numbers are in Black.

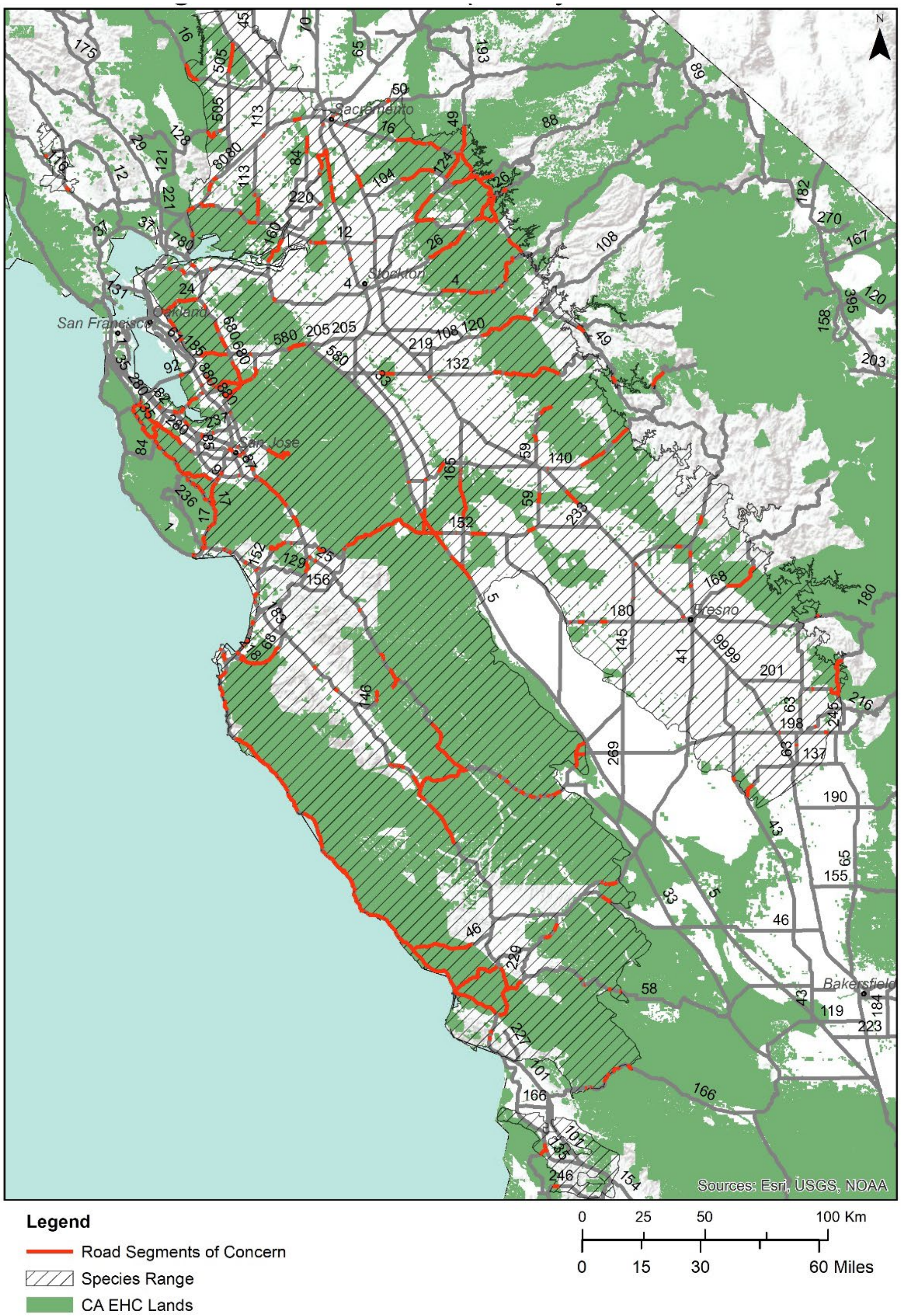

Figure 3. Overlay of Single Very-High Risk Species Range (*Ambystoma californiense*), CEHC Lands and the State Highway System (Elise Watson, USGS). Note: California Highway Numbers are in Black.

Literature Review and Gap Analysis (Task 4)

To synthesize what was currently known about reptile and amphibian crossing systems in California and throughout the world and to identify primary information gaps in scientific and practical knowledge to inform these crossing systems, WTI conducted a detailed literature review and synthesis with input from USGS (Langton and Clevenger 2017). The authors reviewed 52 studies on crossing systems with 125 individual taxa (75 reptile and 50 amphibian species or sub-species) throughout Europe, North America, South America and Australasia. Of these, 45% were for reptiles and 55% amphibians. Information from each paper was summarized into three study or 'knowledge area' categories: passage construction and use, passage environmental variables and barrier construction and use.

Langton and Clevenger (2017) concluded than in most cases road mitigation was installed primarily to reduce road mortality versus to maintain connectivity. However, large passages tended to be more permeable to amphibian and reptile crossings than smaller passages. They determined that the literature reflected a widely spread and low-inference scientific knowledge base regarding the efficacy of amphibian and reptile passages and barrier systems, although the body of literature has been growing in recent years with specific species and systems. They also found little information on the role of existing infrastructure and drainage culverts in helping to maintain genetic and population connectivity for herpetofauna.

Therefore, Langton and Clevenger (2017) concluded there was a need for more properly designed studies to evaluate the effectiveness of purpose-built (engineered) and non-engineered passages and barriers. Research studies (controlled experimental or field settings) were needed to directly measure, test and compare results among mitigation structures, their structural and environmental characteristics, and permeability to species and species groups. Information and knowledge gaps identified from this analysis included the following:

- Use of existing highway structures by herpetofauna.
- Relative permeability of most commonly built structures to different herpetofauna groups.
- Relationship between use and openness ratio and length and width of passage.
- Whether populations could benefit from addition of barrier fencing to existing structures.
- The most effective ways to simulate natural and artificial light, temperature and moisture within underpasses.
- The influence of fence material and opacity on barrier effectiveness and passage use.
- Effectiveness of turnarounds at fence ends.
- The best designs to extend barriers along road access points.

This review and synthesis, along with the risk assessment, was used to help guide field research and for developing California Best Management Practices (BMPs) for sensitive amphibian and reptile highway crossings (Langton and Clevenger 2021).

Research Questions and Field Studies (Task 5)

Based on the literature review and gap analysis, we devised a list of 9 research studies along with research objectives, target species/groups, general study designs, relative costs, and how each of these studies would inform Best Management Practices (BMPs) for Caltrans reptile and amphibian crossings. Representatives from Caltrans (Simon Bisrat, James Henke, Amy Golden, Amy Bailey), Western Transportation Institute (Tony Clevenger, Tom Langton), and USGS (Robert Fisher, Cheryl Brehme) met in September of 2017 to review the study options and select the studies that would be pursued as part of this project.

After reviewing and discussing each of the studies, the following studies were identified as being the most cost effective while providing valuable information for the BMPs. Below are the primary research questions, target species and locations chosen for these studies.

1. What is the maximum distance between passages to maintain permeability for migratory herpetofauna (pond breeding amphibians)?
    a. Target Species/Groups: California tiger salamander, Yosemite toad
    b. Locations: Stanford, Sierra National Forest.

2. How does fence material (transparency) influence species movement along barriers?
    a. Target Species/Groups: reptiles and amphibians, California tiger salamander, Yosemite toad
    b. Locations: San Diego, Stanford, Sierra National Forest

3. Fence ends: How effective are fence-end turnarounds?
    a. Target Species/Groups: reptiles and amphibians
    b. Location: San Diego, Stanford, Sierra National Forest

4. What designs of jump-outs are effective for herpetofauna and other small animals?
    a. Target Species/Groups: reptiles and amphibians
    b. Location: San Diego

Additionally, we included two extra questions in our studies as they developed.

5. What is the relative permeability of a special built passage system for California tiger salamanders (Type 5: Micro-underpass)?
    a. Target Species/Groups: California tiger salamander
    b. Location: Stanford

6. Is there an alternative to the tunnel passage system design for migratory amphibians and other high risk herpetofauna? Evaluation of a novel elevated road segment passage.
    a. Target Species/Groups: Yosemite toad
    b. Location: Sierra National Forest.

Individual reports of all field studies are provided in Chapters 4 through 7.

Summary of Research Findings and Relevance to Caltrans BMP's (Task 6)

The results of our field studies inform the Caltrans Best Management Practices for amphibian and reptile crossing systems regarding passage spacing for migratory amphibians, barrier fencing materials, and the effectiveness of turnarounds and jump-outs. We also evaluated the permeability of an existing amphibian tunnel system and a novel pilot elevated road segment passage.

Movement Distances along Barriers to Inform Passage Spacing for Migratory Amphibians *(Question 1 above)*

Our results from studies of California tiger salamanders (CTS) in Stanford, CA and Yosemite toads in the Sierra National Forest showed that many of these amphibians migrating between wetland and upland habitats were unlikely to reach the road passage systems if they encountered the barrier fencing away from the passage. CTS moved an average distance of 40 m and Yosemite toads moved an average distance of 52 m along barrier fencing before "giving up," and their probability of making it to a crossing decreased rapidly with increasing distance. In addition to distance moved, the direction the salamanders and toads turned when reaching the barrier fencing was a factor in whether they reached a passage. Individuals that reached the barrier fencing and then travelled in the wrong direction (away from the passage) were significantly less likely to reach the crossing than those that made the correct initial direction choice. The average distance moved by these amphibians indicates that approximately half of the individuals moved greater distances and half moved shorter distances before "giving up." We estimated a distance between passages of less than 12.5 m (CTS) and 20 m (Yosemite toads) would be needed along migratory pathways to maintain a high level of permeability.

Therefore, the likelihood by distance that animals reach a passage can inform the planning and spacing of crossing systems for migratory amphibians and other migratory species. Without considering this, amphibian road crossing systems composed of barrier fencing and underpasses have the potential to become a greater barrier to movement. This is particularly relevant when high connectivity is important for the sustainability of the population, such as for migratory amphibian species that must make population level movements between upland and breeding habitats. With non-migratory species, less frequent cross-road movements could be acceptable if roads do not transect seasonal habitats or vital resources. In these cases, occasional crossings to enable reproductive and genetic connectivity may be sufficient to maintain long term population persistence.

Barrier Fencing Materials *(Question 2 above)*

Three of our studies were relevant to herpetofaunal responses to fencing materials of various transparencies. One was the fence trial behavioral study of reptiles in Rancho Jamul, one was our CTS study at Stanford, and the third was our Yosemite toad study in the Sierra Nevada.

The results from our behavioral studies show that herpetofauna are more likely to interact with the transparent and semi-transparent fences by poking at them with their noses, pacing back and forth, and attempting to climb. The transparent (hardware cloth) and semi-transparent fencing (polymer matrix "mesh") used in our studies were not only see-through, but permeable to the movement of air in comparison to plastic solid fencing. Because sight and chemoreception senses are typically well developed in reptiles, it is not clear to what extent these different senses are driving fence interaction behaviors. However, it is clear from our observations that animals exhibiting these behaviors appeared to be trying to find a way through the fence to the other side.

Although fence interaction behaviors have been documented elsewhere in comparing hardware cloth and solid fencing (Ruby et al. 1994, Milburn-Rodríguez et al. 2016), our trial behavioral studies showed a clear gradation of response from solid to semi-transparent to transparent fencing in all taxa studied. In addition, our studies showed that these behavioral responses typically resulted in animals moving slower, or spending more time, along transparent/permeable fencing in comparison to solid fencing. This may not be a large concern when the purpose of the fence is primarily to exclude animals. However, it may be an important consideration when a dual objective is to lead species toward a road crossing structure, particularly when high permeability and population connectivity across the structure is desired.

In our migratory amphibian studies, the transparency of fencing (mesh vs. solid) did not significantly affect the movement distances of CTS or Yosemite toads or their probability of making it to the underpass system, although the estimated probabilities of reaching underpasses were slightly lower for the semi-transparent fencing. With preliminary data, the speed and time of travel for Yosemite toads were not significantly different by fence type. However, for CTS, the speed and time of travel varied significantly by fence type. CTS moving along solid fencing moved at almost twice the average speed and were 3 times less likely to turn around and repeatedly move back and forth. Therefore, CTS moving along fencing that they could see through resulted in them expending a higher amount of time and energy to make it to the crossing.

There are many reasons why different fencing types (hardware cloth, mesh, or solid) may be used in particular landscapes, habitats, and climates with considerations that include heat, rain and wind, permeability, durability, and aesthetics (see Langton and Clevenger 2021). Our behavioral study was the first to show that addition of a simple visual barrier (6 in./153 mm in our study) from the ground upwards, at the base of transparent and semi-transparent fencing, can reduce fence interaction behaviors and increase rates of movement. In fact, for most measures, herpetofauna responses to mesh and hardware cloth fencing with a visual barrier were not significantly different than to the solid barrier. This could allow for more flexibility in the decision-making and planning processes for barrier systems for herpetofauna.

Turnarounds *(Question 3 above)*

Three studies were relevant to the efficacy of turnarounds. One was done in Rancho Jamul, one was our CTS study at Stanford, and the third was our Yosemite toad study in the Sierra Nevada. A general graphic of the turn-around design used is depicted in Figure 4.

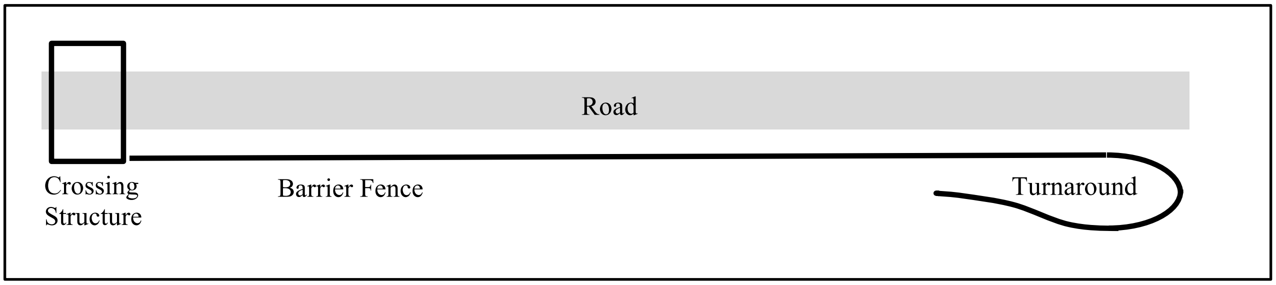

Figure 4. Diagram of Turn-around at Barrier Fence End

Our Rancho Jamul study was the first to show that small turnarounds at fence ends can be effective in changing the trajectory of movement for herpetofauna and small mammals. The turnarounds in our studies were approximately 1.5 m long and 1 m wide at the widest point with the turnaround ending approximately 0.4 m from the original fence line and extending another 0.4 m parallel to the fence. Turnarounds at fence ends were made of hardware cloth, mesh, or solid fencing (2 each). We documented that over 90% of herpetofauna (lizards, snakes and toads) and 69% of small mammals changed course after leaving a turnaround. Of those that changed their trajectory, 67% of herpetofauna and 43% of small mammals moved back along the original fence line while the remainder turned away from the fence line toward the habitat. We previously observed that animals spend more time interacting (e.g. poking, back and forth movements, climbing) with fencing that they can see and smell through (Question 2, Chapter 6). Animals also generally spent increased amounts of time in transparent/permeable and semi-transparent/permeable turnarounds than solid impermeable turnarounds.

Our results also suggest the use of transparent or semi-transparent fencing for turnarounds may increase their effectiveness for some species groups (Chapter 7). These results could be related to animals interacting with the fencing and spending more time in transparent turnarounds, so that they were less likely to remember and continue on their original trajectory. The results may also be related to the different types of spatial learning and memory used for navigation when animals are subjected to solid barriers (egocentric) in comparison to transparent barriers (allocentric) as has been shown in maze-food trials with rodents (Violle et al. 2009, Vorhees and Williams 2014). Validation of these findings in other locations and possibly more specific research studies addressing spatial learning and movement responses in reptiles, amphibians, and small mammals in their natural environments would be needed to further our understanding of these results.

We did not compare different sizes or shapes of turnarounds in our study; however, we hypothesize that having the end of the turnaround close to the original fence line may help to steer animals back along the original barrier in the direction of original origin. Longer or larger turnarounds encompassing smaller turnarounds have been proposed to increase the probability that animals do not go out onto the roadways if they turn away from the fence and into habitat on leaving the turn around (Langton and Clevenger 2021).

In this study, we only documented animal movement for up to 1 m (3.4 feet) after leaving the turnaround. It is entirely possible that animals changed course again after they left the field of view of the video camera. In our Stanford and Sierra movement studies (Chapters 3 and 4), two out of three CTS that presumably reached a turnaround at the fence end were subsequently documented on another camera 25-125 m away moving back along the fence line. Preliminary results suggest seven out of 10 Yosemite toads changed course at a turnaround, while three continued in the direction past the fence ends. Of the seven toads that changed course, four were subsequently documented on another camera 40-80 m away moving back along the fence line toward the passage. Further studies using more cameras and/or tracking methods are needed to better understand how turnarounds affect movement of animals over a longer distances and time frames. Higher mortality of herpetofauna has been well documented at fence ends even with turnarounds (Gunson et al. 2014, Langton and Clevenger 2017, Helldin and Petrovan 2019). However, the high proportion of herpetofauna that changed directions in our study supports the use of turnarounds in attempts to reduce the chances that small animals go out onto the roadway at fence ends and potentially to help 'steer' them back toward to a crossing structure.

Jump-outs *(Question 4 above)*

Animals can get trapped within the roadway if they get through an opening in the fencing or overshoot the end of the fencing. Jump-outs provide a way for animals that get trapped within a roadway surrounded by vertical barrier fencing to safely get back into the habitat on the other side of the fence. Although jump-outs are commonly built structures along wildlife fencing for large mammals, they have not been incorporated into transportation planning for reptile and amphibian barriers. However, short curved or sloped fencing has been designed for amphibians that angles toward the habitat to allow movement over the top in one direction.

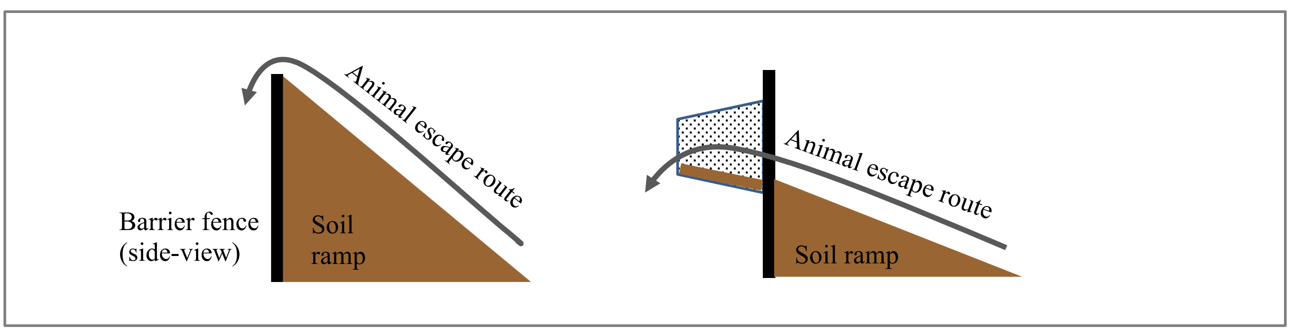

Figure 5. Diagram of Jump-out Configurations a) Over Fence and b) Through Fence.

Our experimental behavioral study showed that two jump-out configurations (Figure 5) were largely effective in allowing animals trapped on the 'wrong' side of a vertical fence to escape back into the habitat. One was simply a soil ramp to the top of the exclusion fencing (Figure 5a: 50 cm. in height) and the other was a polymer box funnel placed at a height of 25 cm above the ground within the exclusion fencing with a small soil ramp leading up to it (Figure 5b). A total of 75% of lizards, 95% of snakes, and 1 of 2 toads used a jump-out to escape the enclosure. There was little difference between the use of the high ramp and low funnel jump-outs by lizards or snakes. We observed that lizards often sat on top of the 50 cm high ramp for long periods of time before jumping to the ground, whereas there was little hesitation with the lower 25 cm jump-outs.

We suggest jump-outs be provided at regular intervals along vertical barriers in the form of a ramp leading to the top of the barrier or leading to a funnel type structure that opens to the habitat. It is also important that any jump-out design for herpetofauna consider the safety of other wildlife. This includes minimizing the size difference of the entrance and exit of box funnel designs so that larger animals do not get stuck in the funnel. Rectangular or cylindrical shapes with the same entry and exit size could be considered. For short barrier fencing, most other wildlife can simply step, climb, or jump over the barrier. For taller barrier fences, escape routes may include jump-outs of several sizes to accommodate a wider variety of species.

Effectiveness of Crossing Structures: Amphibian Tunnels and a Novel Elevated Road Segment *(Questions 5 and 6 above)*

Many small animals, especially amphibian populations that must migrate between aquatic and terrestrial habitats, are susceptible to negative impacts from roads within their habitat (e.g. Hamer et al. 2008, Semlitsch 2008, Brehme et al. 2018). In the winter breeding seasons of 2018 and 2019, we studied the movement of CTS across three existing micro-passage amphibian tunnels spaced approximately 5 m apart from one another along Junipero Serra Blvd in Stanford, CA. The road bisects a historic CTS breeding pond and upland CTS habitat. CTS that did reach the opening of the passage system had a very high probability (87%) of making a complete crossing to the other side. The passages are made of inert materials (polymer concrete) and incorporate a slotted ceiling at the road surface to allow natural light, moisture and rainfall to permeate the length of the passage. These passages have been shown to be permeable to amphibian movement in North America and Europe (Jackson and Tyning 1989, Pagnucco et al. 2012, Langton and Clevenger 2017). Although they have not been used for amphibian passage on the state highway system to date, these results are promising for possible use of these and/or similarly designed passages by Caltrans.

Although micro-passage tunnels are a standard mitigation solution to reduce amphibian road mortality, there is evidence that these systems may filter movements of populations that disperse over large areas, particularly if passages are placed too far apart from one another across the migratory pathways (e.g. Allaback and Laabs 2002, Pagnucco et al. 2012, Ottburg and van der Grift 2019). In 2018 we tested a new and novel passage elevated road segment (ERS) prototype, an eight-in. high elevated road segment using road mats designed for use by heavy equipment at construction sites. The ERS was installed on top of a USFS road along a Yosemite toad mortality "hotspot" with directional barrier fencing. The ERS provides a safe crossing nearly 100 ft wide while allowing both light and rain to pass through. We monitored Yosemite toad and other herpetofaunal activity along fencing and under the passage using specialized cameras. Initial results show that toads and other herpetofauna as well as small mammals used the passage and mortality was greatly reduced. Although the prototype was a 100-ft wide passage, theoretically they could be made to any length. This ERS prototype offers a new concept design to increase permeability of roads to migratory amphibians and other species. There is currently an effort underway by DOT and other transportation engineers to adapt this concept design to more permanent highway applications.

Considerations for Future Studies

To further inform the design of effective barrier and passage systems for herpetofauna, we suggest consideration of the following research:

1. Continue study of Yosemite toads in Sierra National Forest to increase sample size and confidence in model predictions on passage spacing, fence opacity, and the permeability of the ERS crossing system.

2. Include one or more new study locations and species to better predict underpass spacing needs for high-risk migratory amphibian species. This would address the question of whether movement distances along barrier fencing are predictable among species groups and size classes.

3. Continue California tiger salamander and Yosemite toad studies to explore modifications to increase effectiveness of passages. Address the following questions:
    a. Will affixing a visual barrier to transparent or semi-transparent fencing change CTS behavior so that it more closely resembles the reaction to solid fencing? This is useful because in some areas, mesh fencing may be preferred for water/wind permeability, etc.
    b. Would more turnarounds along the length of barrier fencing help to increase the probability of success for animals that start out moving away from tunnels?

4. Continue research to assess the effectiveness of fence end treatments by studying the effect of turnaround length, materials and configuration on amphibian and reptile turnaround rates. Monitor animal movements over longer distances after exiting turnaround.

5. Work with engineers familiar with Caltrans materials and specifications to design (and test if possible) new options to add to existing BMP elements for increasing effectiveness of road crossings for herpetofauna such as:
   a. Elevated road segment (ERS) concept designs for primary roadways.
   b. Artificial lighting in tunnels that best simulates natural lighting for diurnal species. This is mainly for long underpasses where grated skylights in the shoulders and median are not feasible or sufficient to illuminate a passage .
   c. Drip or other drainage systems that deposit a path of moisture in otherwise dry underpasses during rain events.
   d. Design modifications to decrease the temperature differential between tunnel interiors and the surrounding environment.
   e. Design modifications to incorporate cover and ledges for herpetofauna within larger passages.

6. Design and implement studies to better understand if herpetofauna use existing passages and culverts for movement across roads.
   a. If so, what is the relative permeability of the most commonly built structures to different herpetofauna groups?
   b. Is the probability of use related to size of passage? If so, for which species groups?
   c. How is use of passages related to length and openness ratio?
   d. Would barrier fencing increase the use of non-engineered structures (i.e. culverts)?

These proposed studies will allow Caltrans to better evaluate the effectiveness of existing barrier and road crossing systems, to increase the 'toolbox' of innovative solutions, to increase the effectiveness of crossing systems for reptiles and amphibians in California, and to make more informed decisions on underpass spacing for high-risk migratory species.

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References

Note: more extensive citations are included in individual study chapters

Allaback, ML and DM Laabs. 2002. Effectiveness of road tunnels for the Santa Cruz long-toed salamander. Transactions of the Western Section of the Wildlife Society 38: 5–8.

Brehme, CS, SA Hathaway, and RN Fisher. 2018. An objective road risk assessment method for multiple species: Ranking 166 reptiles and amphibians in California. Landscape Ecology 33(6): 911–935.

Caltrans. 2019. Securing Safe Passage for Wildlife. Accessed August 11, 2020. *https://dot.ca.gov/-/media/dot-media/programs/risk-strategic-management/documents/mile-marker/mm-2019-q2-wildlife-crossing-a11y.pdf*.

Gunson, KE, DC Seburn and D. Lesbarrères. 2014. Monitoring turtle movements on Highways 7 & 41; 2012 and 2013. Final report submitted to the Ministry of Transportation, Kingston, Ontario.

Hamer, AJ and MJ McDonnell. 2008. Amphibian ecology and conservation in the urbanising world: a review. Biological Conservation 141(10): 2432–2449.

Helldin, JO and SO Petrovan. 2019. Effectiveness of small road tunnels and fences in reducing amphibian roadkill and barrier effects at retrofitted roads in Sweden. PeerJ 7: p.e7518.

Langton, TES and AP Clevenger 2017. Amphibian and Reptile Highway Crossings: State of the practice, gap analysis and decision support tool. Report prepared for the State of California, Department of Transportation, Division of Research, Innovation and System Information, Office of Materials and Infrastructure Research, June 2017

Langton, TES and AP Clevenger. 2021. Measures to Reduce Road Impacts on Amphibians and Reptiles in California. Best Management Practices and Technical Guidance. Prepared by Western Transportation Institute for California Department of Transportation, Division of Research, Innovation and System Information.

Milburn-Rodríguez JC, J Hathaway, K Gunson, D Moffat, S Béga and D Swensson. 2016. Road mortality mitigation: The effectiveness of Animex fencing versus mesh fencing. *https://animexfencing.com/whyanimex/animex-vs-mesh*

Ottburg, FG and EA van der Grift. 2019. Effectiveness of road mitigation for common toads (*Bufo bufo*) in the Netherlands. Frontiers in Ecology and Evolution, 7, p.23.Hamer, A.J. and McDonnell, M.J., 2008. Amphibian ecology and conservation in the urbanising world: a review. Biological Conservation 141(10): 2432–2449.

Pagnucco KS, CA Paszkowski and GJ Scrimgeour. 2012. Characterizing movement patterns and spatio-temporal use of under-road tunnels by long-toed salamanders in Waterton Lakes National Park, Canada. Copeia 2012(2): 331–340 DOI 10.1643/CE-10-128.

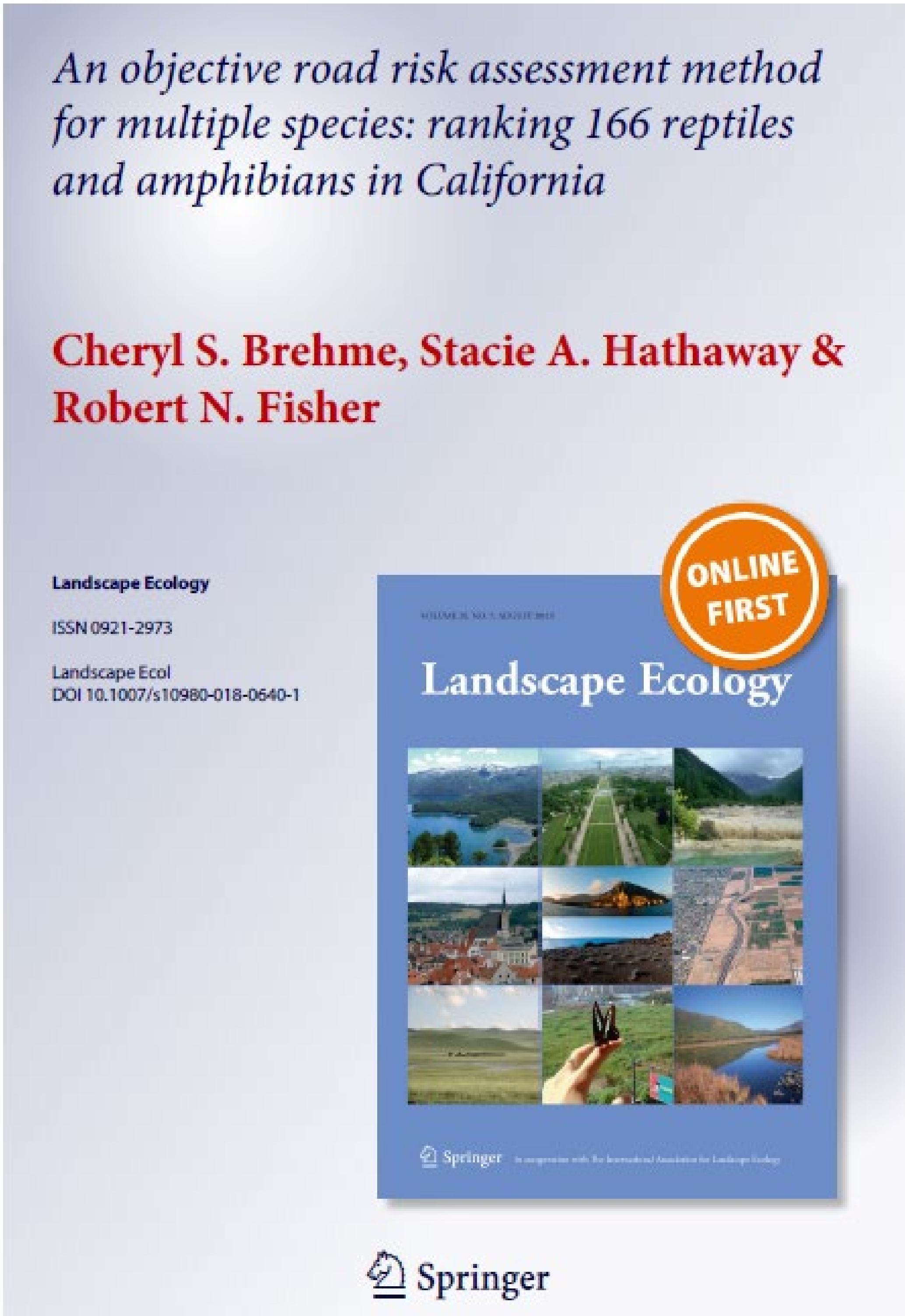
Ruby, DE, JR Spotila, SK Martin and SJ Kemp. 1994. Behavioral responses to barriers by desert tortoises: implications for wildlife management. Herpetological Monographs 8: 144–160.

Semlitsch, RD. 2008. Differentiating migration and dispersal processes for pond-breeding amphibians. Journal of Wildlife Management 72(1): 260–267.

Spencer, WD, P Beier, K Penrod, K Winters, C Paulman, H Rustigian-Romsos, J Strittholt, M Parisi, and A Pettler. 2010. California Essential Habitat Connectivity Project: A Strategy for Conserving a Connected California. Prepared for California Department of Transportation, California Department of Fish and Game, and Federal Highways Administration.

Vorhees, C and MT Williams. 2014. Assessing spatial learning and memory in rodents. ILAR Journal, 55(2), pp. 310–332.

Chapter 2. California Road Risk Analysis for Herpetofauna (Reprinted with permission)



An objective road risk assessment method for multiple species: ranking 166 reptiles and amphibians in California

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RESEARCH ARTICLE

An objective road risk assessment method for multiple species: ranking 166 reptiles and amphibians in California

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Abstract
Context Transportation and wildlife agencies may consider the need for barrier structures and safe wildlife road-crossings to maintain the long-term viability of wildlife populations. In order to prioritize these efforts, it is important to identify species that are most at risk of extirpation from road-related impacts.
Purpose Our goal was to identify reptiles and amphibians in California most susceptible to road mortality and fragmentation. With over 160 species and a lack of species-specific research data, we developed an objective risk assessment method based upon road ecology science.
Methods Risk scoring was based upon a suite of life history and space-use characteristics associated with negative road effects applied in a hierarchical manner from individuals to species. We evaluated risk to both aquatic and terrestrial connectivity and calculated buffer distances to encompass 95% of population-level movements. We ranked species into five relative categories of road-related risk (very-high to very-low) based upon 20% increments of all species scores.
Results All chelonids, 72% of snakes, 50% of anurans, 18% of lizards and 17% of salamander species in California were ranked at high or very-high risk from negative road impacts. Results were largely consistent with local and global scientific literature in identifying high risk species and groups.
Conclusions This comparative risk assessment method provides a science-based framework to identify species most susceptible to negative road impacts. The results can inform regional-scale road mitigation planning and prioritization efforts and threat assessments for special-status species. We believe this approach is applicable to numerous landscapes and taxonomic groups.

Keywords Reptile · Amphibian · Road mortality · Habitat fragmentation · Road ecology · Risk assessment · Road

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Introduction

There have been many attempts to better characterize and quantify threat criteria in order to classify species at higher risk of extinction at state, national, and global levels (Congress 1973 (U.S. Endangered Species Act); Mace et al. 2008; Hobday et al. 2011; Thomson et al. 2016; IUCN 2017). Roads are a significant threat to wildlife populations (e.g., Forman et al. 2003;

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Andrews et al. 2015a; van der Ree et al. 2015), causing both barrier (habitat fragmentation) and depletion (road mortality) effects. Barrier effects occur when animals avoid crossing roads, in which case roads essentially fragment species habitat. Barrier effects include reduced size and quality of available habitat, reduced effective population size, reduced ability to find mates and resources, increased genetic structuring, and increased probability of local extirpation (e.g., Forman et al. 2003; Fahrig and Rytwinski 2009; D'Amico et al. 2016). Depletion effects occur when animals attempt to cross roads and are killed by vehicles. Depletion effects include all of the risks from barrier effects as well as reduced survivorship, making high road mortality an even greater concern (Jackson and Fahrig 2011). Among other stressors, such as habitat loss and fragmentation, invasive species, pesticide use, changing climate, and disease, the negative impacts from roads may independently or cumulatively threaten the persistence of populations and even species.

Amphibians and reptiles have been identified as being particularly susceptible to the negative effects of roads within their habitat (e.g., Klauber 1931; Forman et al. 2003; Rytwinski and Fahrig 2012; Andrews et al. 2015a, b; D'Amico et al. 2015). Many are slow moving, do not avoid roads, and are simply too small for drivers to see and avoid. During rains many amphibians make long linear terrestrial movements regardless of the presence of intersecting roadways (Glista et al. 2008), and because paved roads typically absorb and retain more heat than the surrounding habitat, snakes and lizards are often attracted to roads for thermoregulation (Case and Fisher 2001; Jochimsen et al. 2004). In fact, road surveys are one of the most common methods for surveying these reptiles (e.g., Sullivan 2012). Many herpetofauna species utilize both aquatic and terrestrial habitat for breeding, development, foraging, and overwintering and therefore require connectivity within and between both aquatic and terrestrial habitats to support basic life history requirements.

The primary goal of this study was to provide information to transportation and other planning agencies in California to assist them in prioritizing road mitigation efforts for amphibian and reptile species. Although there is still a lot to learn about the effectiveness of different designs of road mitigation systems, the use of barrier systems, underpasses, and overpasses can reduce road mortality and help to maintain connectivity and safe passage across roads for herpetofauna and other wildlife (Jochimsen et al. 2004; Colino-Rabanal and Lizana 2012; Langton 2015; Langen et al. 2015b). Because it is currently unrealistic and cost prohibitive to mitigate all roadways for all species, it is vital to identify species most susceptible to road-related impacts. Within species ranges, risks to populations and need for mitigation can then be evaluated based upon local road densities and matrix, road-types, traffic, and road locations in relation to species habitat and movement corridors (e.g., Jaeger 2000; Litvaitis and Tash 2008; Langen et al. 2015b; Zimmermann Teixeira et al. 2017).

Here we describe a road risk assessment methodology applied to native amphibian and reptile species in California, a global biodiversity hotspot (Myers et al. 2000). We also included analysis of subspecies if they had special federal or state protection status. This includes 166 species and subspecies of frogs, toads, salamanders, snakes, lizards, turtles, and tortoise. Rankings and prioritizations such as these can be very subjective. In order to avoid including low risk species that may be favored by the assessors or to unintentionally overlook species that are at high risk, it was important for this be done in an objective manner informed by current road ecology literature.

Very few quantitative data are available on the impact of roads on population persistence. Jaeger et al. (2005) were the first to develop a relative ranking system to compare the impact of roads on wildlife populations. Their ranking system was largely based upon behavioral responses of animal species to the road surface, road size, traffic noise, and vehicles with varying road sizes and traffic volumes. However, knowledge of these detailed behavioral responses to ranges in road and traffic characteristics is rarely found in literature and the link between individual behavior and population-level effects has not been clearly established (Rytwinski and Fahrig 2012, 2013).

Rytwinski and Fahrig (2012) performed a meta-analysis of wildlife groups to test whether certain life history characteristics were related to negative responses to roads. High reproductive rate (fecundity) was negatively associated with the magnitude of population-level effects for amphibians. No associations were significant in reptiles, although there were few studies to inform this analysis. However, a strong link was shown between body size, greater mobility, lower reproductive rates and the magnitude of negative road effects in mammals, the most studied wildlife group. Conversely, simulations predicted populations of species with small home ranges and high reproductive rates were the least likely to be affected by roads (Rytwinski and Fahrig 2013).

We used these findings as a basis for creating a multi-tiered system to rank and identify reptile and amphibian species that may be most susceptible to road impacts. We based our ranking upon a suite of species life history and space-use characteristics associated with negative road effects, as well as including species distribution and conservation status. We evaluated risk to both aquatic and terrestrial connectivity and include buffer distances that were calculated to encompass 95% of population movements. Relative confidence in these distances is given for each species based upon the amount of support from scientific studies. We solely focused on the direct effects of roads as barriers and sources of road mortality and not impacts from road construction and maintenance or indirect effects from increased human use of the landscape once a road is in place (see review by Langen et al. 2015a).

Because we based the risk assessment solely upon space-use and life history characteristics, this represents a species relative susceptibility to road impacts. It is understood that circumstances associated with particular populations (e.g., local road types, locations, densities) may elevate or reduce the risk for certain populations and species.

Methods

Road risk assessment (overview)

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

At the individual-level, we based road risk primarily upon the likelihood that an individual would encounter one or more roads. We considered this a product of movement distance (home range, seasonal migrations) and movement frequency (e.g., active foragers, seasonal migrants, sit-and-wait predators vs. sedentary species) (e.g., Bonnet et al. 1999; Carr and Fahrig 2001). Because many species are semi-aquatic, movement distance and frequency were scored separately for both aquatic and terrestrial habitats.

There is a theorized higher risk associated with depletion effects (i.e., road mortality) in comparison to barrier effects (Fahrig and Rytwinski 2009; Jackson and Fahrig 2011). Therefore, we gave additional weight to those species more likely to go out onto a road surface and be killed by vehicular traffic. For this we considered factors of habitat preference (e.g., open vs. closed), roads as potential attractants (e.g., for basking), and movement speed (e.g., slow vs. fast). However, individuals within and among species may respond differently to roads (attraction vs. avoidance) based upon local landscape features, road width, traffic volume, and perceived danger (Forman et al. 2003; Andrews 2005; Brehme et al. 2013; Jacobson et al. 2016). Because a state-wide analysis encompasses extreme variation in landscape and road characteristics, the extent to which roads act as barriers or sources of direct mortality within a species range is unknown. The risk disparity between depletion and barrier effects could also be highly variable. Therefore, we limited the additional weight for potential depletion effects to twenty percent of the individual risk score.

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

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

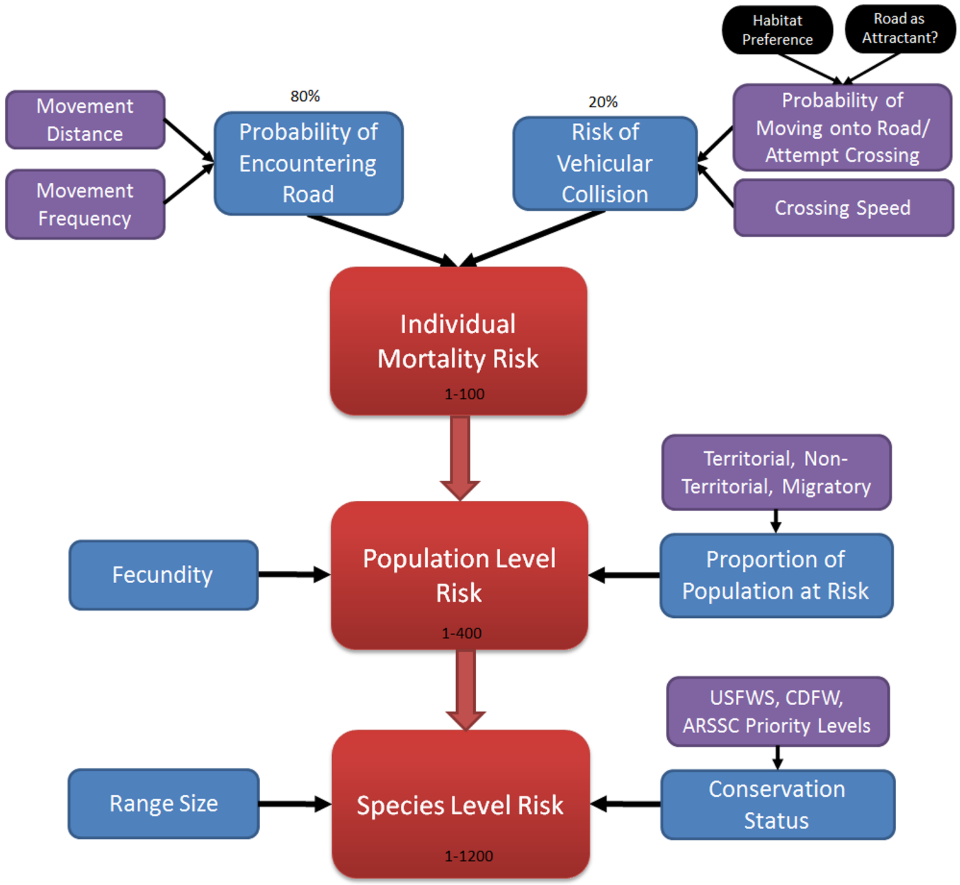

Fig. 1 California reptile and amphibian road risk assessment conceptual model (*ARSSC* Amphibian and Reptile Species of Special Concern (Thomson et al. 2016))

multiple stressors, and are thus thought to be less likely to be resilient to additional road impacts.

Although we present both aquatic and terrestrial risk scores for semi-aquatic species, we used the higher of the two scores for the overall risk ranking.

Literature review

Species life history data were primarily taken from and cross-checked among the following species account review sources;

1. U.S. Fish and Wildlife Service (USFWS) Recovery Plans and 5-year Reviews https://www.fws.gov/endangered/.
2. California Amphibian and Reptile Species of Special Concern (ARSSC; Thomson et al. 2016).
3. A Field Guide to Amphibians and Reptiles of California (Stebbins and McGinnis 2012)
4. Amphibian declines: the conservation status of United States species (Lannoo 2005).
5. Conservation Status of Amphibians and Reptiles on USDA National Forests, Pacific Southwest Region, 2012 (Evelyn and Sweet 2012).
6. Natureserve Explorer (natureserve.org): Species Accounts largely authored by G. Hammerson (2003–2016).

When these reviews were lacking life history information needed for the road risk assessment, we then searched for supplementary peer-reviewed literature using the Google Scholar search engine. Because movement distances (terrestrial, aquatic, home range, migratory) were so important for the risk assessment, we acquired referenced articles from the species accounts and independently searched the literature to acquire these data. Search terms included the species common name, scientific name, or genus and terms such as “movement”, “home-range”, “spatial”, and “telemetry”. We also reviewed articles for citations of other studies to find more recent information on movement. This literature included published articles, book chapters, M.S. Theses, Ph.D. dissertations, agency reports, and consultant reports. In the case that specific life history or movement information was not found for a species, we chose a surrogate species based upon phylogeny, habitat, and body size. We first looked for the closest related species within the genus or family and chose a closely related surrogate based upon similar habitat and body size. If surrogates were used, these are clearly reported.

Road risk metrics

The following section describes in detail the rank scoring used for Individual-level Road Risk, Population-level Road Risk, and Species-level Road Risk. All rank values are meant to represent the relative contribution of each attribute to either additive or multiplicative road risk.

Individual-level risk (100 points possible)

Out of a total of 100 points for individual road mortality risk, we attributed up to 80 points (80%) to the risk of encountering a road and up to 20 points (20%) for the risk of an individual moving onto a road and being killed by a motor vehicle.

The risk of encountering a road was based on a combination of movement distance and general movement frequency. Movement distance was ranked 1–40 based upon home range movement distances (diameter) for non-migrants or migration distances for seasonal migrants that spanned from 0 to > 1200 m (Table 1). The scores are linearly correlated with increasing movement distance.

For species that use both terrestrial and wetland/stream/riverine habitats, such as frogs, toads, aquatic snakes and turtles, we scored aquatic and terrestrial movement distances and frequencies separately. This was necessary as some species move much larger distances and at different frequencies in one habitat versus the other. This also informs the type(s) of mitigation structures that may be warranted based upon habitat type, buffer distances and risk scores for each species. Aquatic movement distances were not calculated for pond-breeding amphibians. Ponds are typically small ephemeral bodies of water and terrestrial movements of amphibians to and among ponds account for the majority of movement for these species.

Table 1 Individual-level Road Risk (IRR): Score criteria for risk of individuals encountering a road

Risk of individuals encountering a road = Movement distance × frequency

Movement distance (m)	Score	Frequency	Score
> 1200	40	Active throughout home range	2
901–1200	32	Migratory (2–4 × per year)/ non-migratory sit and wait foragers	1.5
601–900	24	Sedentary, confined to specialized habitat	1
451–600	16		
301–450	12		
201–300	8		
101–200	5		
51–100	3		
0–50	1		

The calculations and rankings for movement distances were well considered and deserve further explanation. Our original thinking was that maximum distances should reflect relative movement distances across species and these data were commonly reported in species accounts. However, it became increasingly difficult to determine whether maximum distances reported were seasonal migration movements, home range movements or rarer dispersal events. We believed this assessment should reflect annual movement distances and not rare dispersal events. We considered using average/median movement distances; however, these often underestimate the movement of seasonal migrants because in many cases a sizeable portion of the population may remain close to a breeding site, while another sizable portion make longer distance migrations causing an average or median to be uninformative. Therefore, we decided to use a buffer distance that incorporates the movement distances of 95% of the population studied. A 95% population movement distance is commonly accepted for the delineation of terrestrial buffer zones for amphibians (i.e., Semlitsch 1998; Semlitsch and Bodie 2003) and we believe it was the most biologically meaningful and useful measure for this study. This measure, which we will refer to as Maximum Population Movement Distance (MPMD), should include almost all population movements, such as seasonal migration distances and annual home ranges (diameter), but not rare dispersal events. The MPMD should also be useful for local risk assessments as these distances can be used to aide in mapping and mitigation decisions.

The calculation we used for MPMD is commonly known as the 95% upper tolerance interval (Vangel 2015). A tolerance interval is an interval that is meant to contain a specified percentage of individual population measurements. This should not be confused with a confidence interval, which is an interval that is meant to contain the population mean. We chose a 50% confidence level for the upper 95% confidence limit of movement distances which is equal to the 95% prediction interval for future observations and is the mean + 1.645 × standard deviation. In cases where a standard deviation was not reported, we back calculated standard deviation from the standard error and sample size, calculated it from the individual data, or estimated it based on the methods recommended by Hozo et al. (2005). Although non-parametric tolerance intervals would be more appropriate for non-normally distributed movement data, the data required to calculate these is rarely reported in the published literature. In the case of non-normally distributed data where medians, sample sizes and ranges are reported, Hozo et al. (2005) methods allow for approximation of means and standard deviations with no assumption of the underlying data distribution. We found the resulting MPMDs to be reasonable in excluding large outliers but including multiple long distance movements below the maximum movement distance.

We recognize that for any species there can be substantial variability in movement distances that depend upon varying local, landscape, and climatic factors. This was often reflected in studies with sometimes widely varying estimates of home range and migration distances. We attempted to be conservative by using the study data for calculation of MPMD in which the largest population movement distances were observed. For studies where movement distance significantly varied between females and males, we used the information from the wider ranging sex. For migratory distances, we did not use distances from extreme environments, such as Canada, where suitable overwintering sites are typically much farther away from breeding and summer activity areas than in milder California climates (e.g., Gregory 1984). We did use study data from adjacent states or lower estimates of migration distances from those reported in Midwestern states. In some cases where little information was available, we made an educated guess based upon limited study data and/or closely related species and noted these in the tables. For all MPMDs, we report a relative confidence level based upon the number and quality of studies, sample sizes, and locations in or adjacent to California. It is intended that the scores be adjusted as new information becomes available.

To compute the risk of encountering a road, the MPMD was multiplied by a relative index of the expected frequency of longer distance movements (1–2 points; Table 1). We defined three frequency categories largely based upon annual migratory movements or foraging strategies for non-migratory species. The highest category included actively foraging predators which are characterized by frequent wandering movements throughout their home range (Pianka 1966). Less frequent movers included seasonal migrants traveling among breeding, summer foraging, and/or overwintering sites and non-migratory 'sit-and-wait' predators that remain still for long periods of time to ambush prey (Pianka 1966). Finally, low frequency included highly sedentary species with high site fidelity, particularly specialized rock, crevice, soil, or tree dwellers that may rarely traverse terrestrial or aquatic habitats.

The risk of an individual moving onto a road and being killed by a moving vehicle was ranked by attributes of habitat preference, road use, and movement speed (Table 2). Habitat preference represents the degree to which an individual is expected to go out onto or avoid an open road as predicted from their habitat and microhabitat preferences. Open habitat specialists and generalists were expected to more readily move onto a road than species that prefer cover (e.g., Forman et al. 2003; Brehme et al. 2013). Although many amphibians are closed habitat specialists, most readily move through open habitats during rain events, when most overland migratory movements tend to occur (Glista et al. 2008). Therefore, amphibians were considered open habitat specialists for this ranking. An additional factor that may increase road use is for thermoregulation for lizards

Table 2 Individual-level Road Risk (IRR): Score criteria for risk of road mortality

Risk of road mortality = Habitat preference + road use + movement speed					
Habitat preference	Score	Road use	Score	Movement speed	Score
Open habitat specialist/amphibians	10	Thermoregulation (snakes/lizards)	4	Slow (< 0.6 m/s)	6
Generalist	8	Other	0	Medium (0.6–2.0 m/s)	3
Edge specialist	4			Fast (> 2.0 m/s)	0
Closed habitat or aquatic specialist	0				

Table 3 Population-level Road Risk (PRR): Score criteria for population level road risk

PRR = IRR × (Fecundity + Proportion of population at risk)				
Fecundity	Ave. potential offspring/year	Score	Proportion of population at risk	Score
Low	0–10	2	Seasonal migrants (Migratory)	2
Med	11–25	1.5	Wandering	1.5
High	26–100	1	Territorial	1
Very high	> 100	0		

and snakes, as roads often retain more heat than the surrounding environment (Colino-Rabanal and Lizana 2012; Mccardle and Fontenot 2016). Finally, there is an increased risk of road mortality for slow versus fast moving species (see Andrews and Gibbons 2005; Mazerolle et al. 2005; Andrews et al. 2015b).

Population-level Road Risk (400 points possible)

To assess the risk of negative road impacts on the persistence of a population we incorporated scores for population-level movement behavior and fecundity (Table 3). For the proportion of a population expected to encounter a road, we scored the greatest risk to species that seasonally migrate to overwintering and breeding areas (Jackson et al. 2015). For those that do not migrate, we expected higher proportions of non-territorial or loosely territorial species ("wandering") to encounter roads than species that defend distinct territories.

Species with low fecundity are less resilient to road mortality impacts than highly fecund species (Rytwinski and Fahrig 2013). Relative fecundity was simply calculated from the average number of potential offspring per year whether the animals were oviparous or live-bearing. For egg-laying species, the number of potential offspring was calculated by multiplying the average clutch size by the average number of clutches per year.

Individual mortality risk (1–100 points) was multiplied by the sum of these population-level factors (1–4 points) to calculate population-level road risk.

Species-level road risk (1200 points possible)

In comparison to population-level risk, we considered the overall risk of roads to species to be negatively associated with species range and conservation status. Although some populations may be at high risk, species with a wide distribution and many populations should be more resilient to localized declines and extirpations. Therefore, we assigned a range isolation score ranging from 0 to 1 that considered species distributions range-wide (North America) and within California (CA) (Table 4). Range-wide distribution varied from "CA only" to "widespread" (> 4 states). If the species range extended into Mexico and/or Canada, these countries were counted as another state for calculation of the index. California-wide distribution was calculated based upon the number of CA geographic regions occupied out of twelve regions defined by Hickman (1993) and used in Stebbins and

Table 4 Species-level Road Risk (SRR): Score criteria for species-level road risk

SRR[a] = PRR × ((Range isolation score + Conservation status score)/2)	
(a) Range isolation score = (North America range + CA range)/2	
North America range	Rank/score
CA only	1.00
2 states (very restricted distribution)	1.00
2 states (restricted)	0.67
2–3 states	0.33
Widespread (4 + states)	0.00
California range (No. of geographic regions occupied)	Rank/score
1	0.92
2	0.83
3	0.75
4	0.67
5	0.58
6	0.50
7	0.42
8	0.33
9	0.25
10	0.17
11	0.08
12	0.00
(b) Conservation status score	
Conservation status	Rank/score[a]
CA or federal threatened/endangered	1.00
SSC priority 1	0.75
SSC priority 2	0.50
SSC priority 3	0.25
None	0.00

[a]Population-level risk > 80 only

McGinnis (2012). These two scores (Range-wide isolation, CA isolation) were summed and divided by two in order to normalize the overall range isolation score to a 0 to 1 scale.

At the species-level, we also incorporated conservation status (Table 4). Some species are declining and are at higher risk of extinction often due to multiple stressors. Federal and State Threatened and Endangered Species were given the highest score (1.0). In California, forty-five species are designated "Species of Special Concern (SSC)" with a ranking of 1, 2, or 3 based upon severity and immediacy of threats affecting each taxon (Thomson et al. 2016). SSC species were given a conservation status score ranging from 0.25 to 0.75 based upon their SSC ranking. Population-level Road Risk (score range 1–400) was multiplied by (1 + Range Isolation Score + Conservation Status Score; score range 1–3) to calculate the final Species-level Road Risk.

Range and conservation status were only used as a multiplier for species-level road risk if the population-level road risk was greater than 80 (20% of possible population score). This helped to prevent false inflation of the road risk metrics for low road susceptible species.

Because all members of the genus *Batrachoseps* (slender salamanders) are similar in body size, range size and general life history characteristics, we scored

Table 5 Species-level frequency distributions and road risk rankings

Percentile	Scores	Relative ranks
81–100	322–710	Very high
61–80	213–321	High
41–60	63–212	Medium
21–40	53–62	Low
1–20	0–52	Very Low

the genus as whole with the most conservative estimates and conservation status but included all 20 species in the final count and calculations.

Once all 166 species (including subspecies with conservation status) were scored for species-level road risk within both terrestrial and aquatic habitats, we took the maximum score for each species and sorted them from the highest to lowest scores. We grouped species into categories of risk (Very high, high, medium, low, and very low) based upon ranges of values that represented frequency distributions in 20% increments of all species scores (Table 5, Fig. 2).

As a way to support the results of our ranking model with species literature, we focused on special status species. We reviewed recovery plans and 5-year reviews for federally listed species and state species accounts for California listed species and species of special concern (collectively referred to as special status species). For each rank group (i.e., “very low” to “very high”), we calculated the percentage of special status species where roads were specifically listed as a threat. Similarly, we tallied the number of species identified in a recent California preliminary road risk assessment (Levine 2013, Amy Golden pers. comm.) and compared the number of species that fell within each of our road risk categories.

Results

All chelonids, 72% of snakes, 50% of anurans, 18% of lizards and 17% of salamander species were ranked as high or very high risk from negative road impacts. (Table 6, Fig. 3).

Review of species accounts, recovery plans, and 5-year reviews for all special status species showed

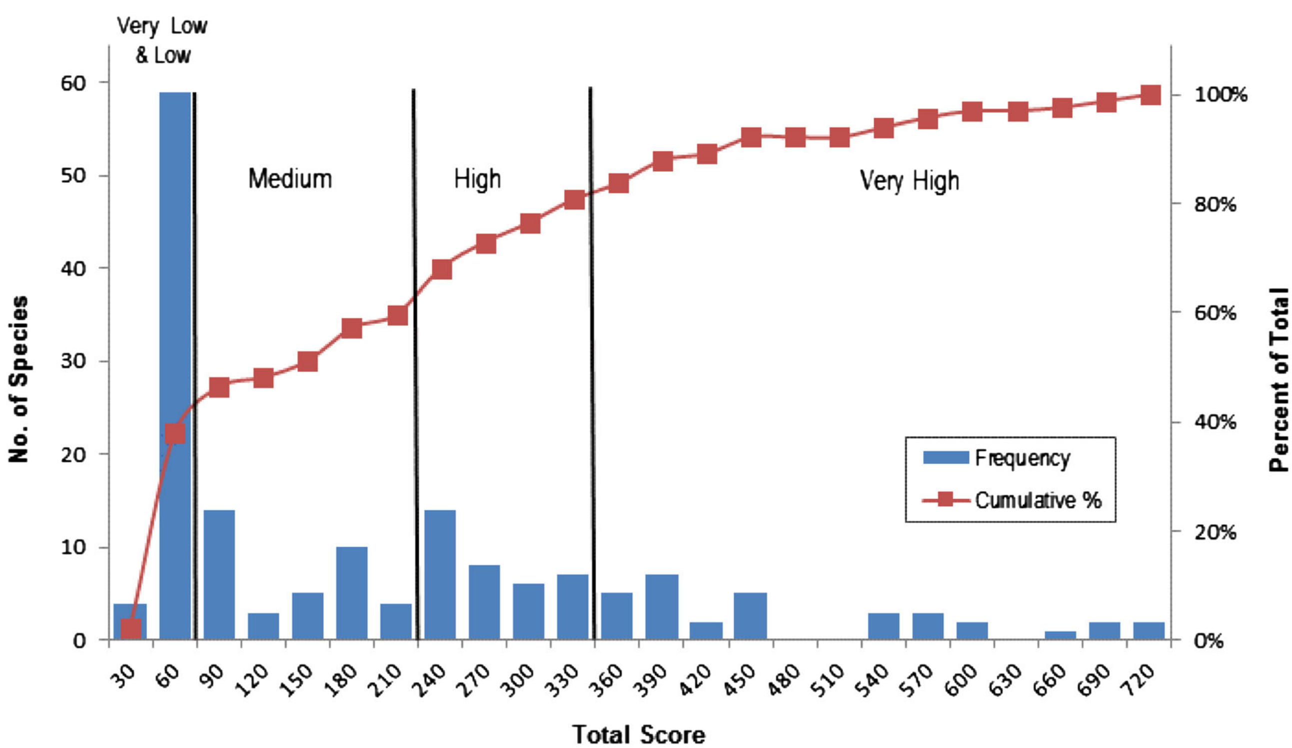

Fig. 2 Histogram of species-level scores and approximate 20 percentile road risk categories

Table 6 Numbers of species by taxa within each risk category

Species group	Species-level rankings				
	Very high	High	Med	Low	Very low
Salamander	4	4	3	26	9
Lizard	5	3	8	7	21
Anuran	5	6	6	4	1
Snake	15	21	13	0	1
Tortoise	1	0	0	0	0
Turtle	3	0	0	0	0

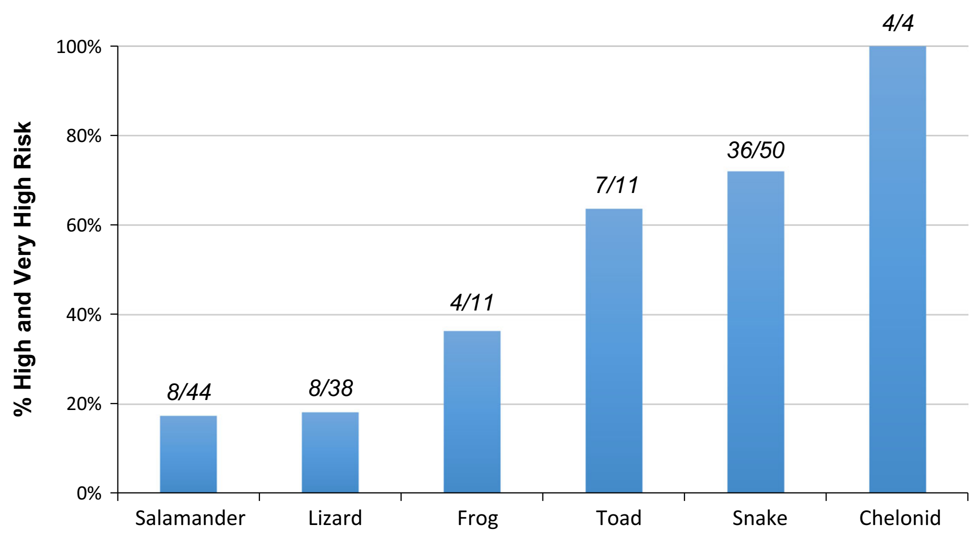

Fig. 3 Percentages of species by taxa in high and very high road risk categories

that 94% (17/18) of species accounts that referenced roads as a threat to the species were ranked as "high" or "very high" in our risk assessment (Table 7). Of the special status species that ranked 'high' and 'very high', close to fifty percent (17/35) had road-related threats referenced in their listing literature. In comparison, only 4% (1/27) of 'medium' to 'very low' risk special status species accounts mentioned roads as a potential threat. In addition, 79% (15/19) of species of concern recommended in a recent Caltrans preliminary road risk assessment scored as 'high' or 'very high' risk in our analysis (Levine 2013, Amy Golden pers. comm.).

Table 7 Comparison of road risk results and number of special status species with roads listed as threat

Road risk level	Special status species			Caltrans PI[a]
	No. species in road risk level	No. species with roads listed as threat	% of Total	No. Spp in road risk level
Very high	25	14	56	11
High	11	3	27	4
Medium	5	1	20	3
Low	10	0	0	1
Very low	7	0	0	0

[a]Caltrans PI are Caltrans identified sensitive species

Table 8 Amphibian and reptile road risk assessment: very high risk species (80–100% percentile), high risk species (60–80% percentile), medium risk species (40–60% percentile range), low risk species (20–40% percentile) and very low risk species (0–20% percentile)

	Species			Road Risk Scores			Status		
Risk Level-Species	Group	Common Name	Scientific name	Maximum (Aquatic & Terrestrial)[a]	Terrestrial	Aquatic (Wetlands/ Rivers/ Streams, Perennial to Intermittent)	Federal or State Listing/ ARSSC Priority Rank (1-3)[b]	Roads Listed as Potential Threat in Listing?[c]	Caltrans Identified Sensitive Species?[d]
Very High	Snake	Giant Gartersnake	*Thamnophis gigas*	710	44	710	THR	Yes	Yes
	Turtle	Southern Western Pond Turtle	*Actinemys pallida*	707	283	707	1		Yes
	Snake	San Joaquin Coachwhip	*Masticophis flagellum ruddocki*	689	689	-	2	Yes	
	Snake	San Francisco Gartersnake	*Thamnophis sirtalis tetrataenia*	663	238	663	END		Yes
	Snake	Alameda Striped Racer	*Masticophis lateralis euryxanthus*	652	652	-	THR	Yes	
	Snake	California Red-sided Gartersnake	*Thamnophis sirtalis infernalis*	588	211	588	1		
	Tortoise	Mohave Desert Tortoise	*Gopherus agassizii*	580	580	-	THR	Yes	Yes
	Salamander	Red-bellied Newt	*Taricha rivularis*	561	561	72	2	Yes	Yes
	Turtle	Northern Western Pond Turtle	*Actinemys marmorata*	547	219	547	3		Yes
	Snake	Two-striped Gartersnake	*Thamnophis hammondii*	541	195	541	2		
	Snake	Baja California Coachwhip	*Masticophis fuliginosus*	534	534	-	3	Yes	
	Snake	Coast Patch-nosed Snake	*Salvadora hexalepis virgultea*	533	533	-	2	Yes	
	Salamander	California Newt	*Taricha torosa*	532	532	72	2	Yes	Yes
	Lizard	Banded Gila Monster	*Heloderma suspectum cinctum*	446	446	-			
	Salamander	California Tiger Salamander	*Ambystoma californiense*	437	437	-	THR	Yes	Yes
	Salamander	Sierra Newt	*Taricha sierrae*	437	437	72			
	Snake	Striped Whipsnake	*Masticophis taeniatus*	425	425	-			
	Lizard	Flat-tail Horned Lizard	*Phrynosoma mcallii*	425	425	-	2	Yes	
	Turtle	Sonoran Mud Turtle	*Kinosternon sonoriense*	399	37	399	1		
	Lizard	Blunt-nosed Leopard Lizard	*Gambelia sila*	393	393	-	END	Yes	Yes
	Snake	Baja California Ratsnake	*Bogertophis rosaliae*	387	387	-			
	Snake	Panamint Rattlesnake	*Crotalus stephensi*	387	387	-			
	Frog	California Red-legged Frog	*Rana draytonii*	380	380	300	THR	Yes	Yes
	Toad	Yosemite Toad	*Anaxyrus canorus*	379	379	284	THR	Yes	
	Toad	Black Toad	*Anaxyrus exsul*	379	379	284	THR		
	Lizard	Cope's Leopard Lizard	*Gambelia copeii*	372	372	-	2		
	Toad	Sonoran Desert Toad	*Incilius alvarius (Possibly extinct in CA)*	361	361	285	1		
	Lizard	Desert Horned Lizard	*Phrynosoma platyrhinos*	356	356	-			
	Snake	California Glossy Snake	*Arizona elegans occidentalis*	340	340	-	1		
	Snake	North American Racer	*Coluber constrictor*	334	334	-			
	Snake	Coachwhip	*Masticophis flagellum*	333	333	-			
	Toad	Arroyo Toad	*Anaxyrus californicus*	331	331	248	END	Yes	Yes
	Snake	Striped Racer	*Masticophis lateralis*	322	322	-			

[a] Maximum scores color-coded for toad risk type; terrestrial (gray), aquatic (blue), or both (gray/blue)
[b] END=Endangered, THR= Threatened, 1-3= ARSSC Priority Ranking
[c] Federal Recovery plans, 5-year reviews, California species accounts for special status species
[d] California Amphibian and Reptile Crossing Preliminary Investigation

Risk scores and relative rankings for California reptile and amphibian species in both terrestrial and aquatic habitats are presented in Tables 8. Terrestrial and Aquatic rankings are provided separately in Tables 9 and 10 and also include population-level risk scores, 95% population buffer distances, confidence levels, and identification of any surrogate species used for the distance calculations. Species scores for all ranking criteria and life history and movement references are provided in Appendices 1 and 2.

Discussion

To our knowledge, this is the first attempt to objectively assess the relative risk of roads at a species level using a logical and scientifically based framework and apply it across a large array of species and habitats. We believe this approach could be useful for assessing and comparing susceptibility of species to negative road impacts within and among all taxonomic groups. To date, such risk assessments have been based largely upon expert opinion, limited information available on

Table 8 continued

Risk Level-Species	Species			Road Risk Scores			Status		
	Group	Common Name	Scientific name	Maximum (Aquatic & Terrestrial)[a]	Terrestrial	Aquatic (Wetlands/ Rivers/ Streams, Perennial to Intermittent)	Federal or State Listing/ ARSSC Priority Rank (1-3)[b]	Roads Listed as Potential Threat in Listing?[c]	Caltrans Identified Sensitive Species?[d]
High	Snake	Red Diamond Rattlesnake	*Crotalus ruber*	321	321	-	3	Yes	
High	Snake	Speckled Rattlesnake	*Crotalus mitchellii*	317	317	-			
High	Frog	Oregon Spotted Frog	*Rana pretiosa (Possibly extinct in CA)*	315	41	315	THR		
High	Salamander	Santa Cruz Long-toed Salamander	*Ambystoma macrodactylum croceum*	308	308	-	END	Yes	Yes
High	Salamander	Rough-skinned Newt	*Taricha granulosa*	304	304	72			
High	Snake	Sierra Gartersnake	*Thamnophis couchii*	304	44	304			
High	Snake	Regal Ring-necked Snake	*Diadophis punctatus regalis*	298	298	-	2		Yes
High	Snake	California Lyresnake	*Trimorphodon lyrophanes*	293	293	-			
High	Frog	Northern Red-legged Frog	*Rana aurora*	291	291	230	2		Yes
High	Snake	Mojave Rattlesnake	*Crotalus scutulatus*	276	276	-			
High	Snake	Western Patch-nosed Snake	*Salvadora hexalepis*	276	276	-			
High	Snake	Common Gartersnake	*Thamnophis sirtalis*	271	165	271			
High	Snake	Aquatic Gartersnake	*Thamnophis atratus*	266	40	266	0		
High	Snake	Sidewinder	*Crotalus cerastes*	263	263	-			
High	Salamander	California Giant Salamander	*Dicamptodon ensatus*	260	260	72	3	Yes	
High	Snake	Sonoran Lyresnake	*Trimorphodon lambda*	260	260	-			
High	Snake	Western Rattlesnake	*Crotalus oreganus*	250	250	-			
High	Snake	Northwestern Gartersnake	*Thamnophis ordinoides*	245	138	245			
High	Snake	Desert Nightsnake	*Hypsiglena chlorophaea*	241	241	-			
High	Snake	Western Terrestrial Gartersnake	*Thamnophis elegans*	240	75	240			
High	Lizard	Switak's Banded Gecko	*Coleonyx switaki*	236	236	-	THR		
High	Toad	Western Spadefoot	*Spea hammondii*	234	234	-	1		Yes
High	Snake	Coast Nightsnake	*Hypsiglena ochrorhyncha*	233	233	-			
High	Lizard	Long-nosed Leopard Lizard	*Gambelia wislizenii*	226	226	-			
High	Toad	Great Plains Toad	*Anaxyrus cognatus*	222	222	175			
High	Toad	Woodhouse's Toad	*Anaxyrus woodhousii*	222	222	175			
High	Lizard	Coastal Whiptail	*Aspidoscelis tigris stejnegeri*	219	219	-	2		
High	Snake	Western Shovel-nosed Snake	*Chionactis occipitalis*	218	218	-			
High	Snake	Spotted Leaf-nosed Snake	*Phyllorhynchus decurtatus*	218	218	-			
High	Salamander	Southern Long-toed Salamander	*Ambystoma macrodactylum sigillatum*	217	217	-	2		
High	Frog	Cascades Frog	*Rana cascadae*	217	217	72	2		
High	Snake	Western Diamond-backed Rattlesnake	*Crotalus atrox*	214	214	-			
High	Snake	Western Groundsnake	*Sonora semiannulata*	212	212	-			

[a] Maximum scores color-coded for toad risk type; terrestrial (gray), aquatic (blue), or both (gray/blue)
[b] END=Endangered, THR= Threatened, 1-3= ARSSC Priority Ranking
[c] Federal Recovery plans, 5-year reviews, California species accounts for special status species
[d] California Amphibian and Reptile Crossing Preliminary Investigation

road mortality, and even less information available on population or species-level road effects (Levine 2013; Rytwinski and Fahrig 2015).

Overall, this is meant to be a first step in highlighting reptile and amphibian species that may be at highest risk from roads transecting their habitat. These species may deserve consideration for further study and for implementing mitigation solutions to reduce mortality and to maintain or enhance connectivity. The risk assessment was done for both terrestrial and aquatic habitats to further inform mitigation. Some aquatic species may greatly benefit from fish passages while others may better benefit from terrestrial barriers and wildlife crossings or both.

Although data are currently lacking to validate completely the scoring and results of the risk assessment, our review of species accounts, recovery plans, 5-year reviews for federal and state-listed species and California species of special concern show a strong association between elevated road risk from our

Table 8 continued

	Species			Road Risk Scores			Status		
Risk Level-Species	Group	Common Name	Scientific name	Maximum (Aquatic & Terrestrial)[a]	Terrestrial	Aquatic (Wetlands/ Rivers/ Streams, Perennial to Intermittent)	Federal or State Listing/ ARSSC Priority Rank (1-3)[b]	Roads Listed as Potential Threat in Listing?[c]	Caltrans Identified Sensitive Species?[d]
Medium	Snake	Checkered Gartersnake	*Thamnophis marcianus*	210	69	210			
	Lizard	Blainville's Horned Lizard	*Phrynosoma blainvillii*	209	209	-	2		Yes
	Frog	Foothill Yellow-legged Frog	*Rana boylii*	199	26	199	1		
	Snake	Gopher Snake	*Pituophis catenifer*	189	189	-			
	Snake	California Mountain Kingsnake	*Lampropeltis zonata*	184	184	-			Yes
	Snake	Glossy Snake	*Arizona elegans*	180	180	-			
	Lizard	Pygmy Short-horned Lizard	*Phrynosoma douglasii*	179	179	-			
	Toad	Couch's Spadefoot	*Scaphiopus couchii*	178	178	-	3		
	Snake	California Kingsnake	*Lampropeltis californiae*	175	175	-			
	Snake	Long-nosed Snake	*Rhinocheilus lecontei*	165	165	-			
	Toad	Western Toad	*Anaxyrus boreas*	165	165	130			
	Snake	Ring-necked Snake	*Diadophis punctatus*	164	164	-			Yes
	Lizard	San Diego Banded Gecko	*Coleonyx variegatus abbotti*	158	158	-	3	Yes	
	Salamander	Northwestern Salamander	*Ambystoma gracile*	152	152	-			
	Toad	Great Basin Spadefoot	*Spea intermontana*	152	152	-			
	Toad	Red-spotted Toad	*Anaxyrus punctatus*	147	147	72			
	Salamander	Long-toed Salamander	*Ambystoma macrodactylum*	143	143	-			
	Lizard	Orange-throated Whiptail	*Aspidoscelis hyperythra*	137	137	-			
	Snake	Smith's Black-headed Snake	*Tantilla hobartsmithi*	136	136	-			
	Snake	California Black-headed Snake	*Tantilla planiceps*	133	133	-			
	Lizard	Western Whiptail	*Aspidoscelis tigris*	118	118	-			
	Salamander	Coastal Giant Salamander	*Dicamptodon tenebrosus*	117	117	48			
	Lizard	Western Banded Gecko	*Coleonyx variegatus*	105	105	-			
	Lizard	Common Chuckwalla	*Sauromalus ater*	78	78	-			
	Snake	Northern Rubber Boa	*Charina bottae*	77	77	-			
	Snake	Southern Rubber Boa	*Charina umbratica*	77	77	-	THR		
	Snake	Northern Three-lined Boa	*Lichanura orcutti*	77	77	-			
	Lizard	Desert Iguana	*Dipsosaurus dorsalis*	72	72	-			
	Snake	Forest Sharp-tailed Snake	*Contia longicauda*	70	70	-			
	Snake	Common Sharp-tailed Snake	*Contia tenuis*	70	70	-			
	Frog	Pacific Treefrog	*Pseudacris regilla*	68	68	36			

[a] Maximum scores color-coded for toad risk type; terrestrial (gray), aquatic (blue), or both (gray/blue)
[b] END=Endangered, THR= Threatened, 1-3= ARSSC Priority Ranking
[c] Federal Recovery plans, 5-year reviews, California species accounts for special status species
[d] California Amphibian and Reptile Crossing Preliminary Investigation

objective analysis and the probability that roads are listed as a potential threat to the species in the species listing literature.

Although more than 40% of special status species are semi-aquatic, roads were rarely considered a threat to aquatic connectivity in the species literature. This may be accurate if bridges or large culverts currently exist for water flow that also provide permeability to aquatic movement. Bridges are generally considered to be completely passable by all aquatic species. Bridges are more likely to be constructed adjacent to or over large water bodies and rivers, presumably resulting in less risk to aquatic movement of populations that inhabit lake and river systems. However, culverts that are more commonly constructed under roads in streams and wetlands vary in passability depending on factors such as diameter, length, slope, outlet configuration, and other characteristics (Furniss et al. 1991; Clarkin et al. 2005; Kemp and O'Hanley 2010). In fact, Januchowski-Hartley et al. (2013) found that only 36% of road crossings were fully passable to fish in the Great Lakes basin. In addition, many low water crossings in arid regions of the state are simply a dip in the road that allows water to flow

Table 8 continued

	Species			Road Risk Scores			Status		
Risk Level-Species	Group	Common Name	Scientific name	Maximum (Aquatic & Terrestrial)[a]	Terrestrial	Aquatic (Wetlands/ Rivers/ Streams, Perennial to Intermittent)	Federal or State Listing/ ARSSC Priority Rank (1-3)[b]	Roads Listed as Potential Threat in Listing?[c]	Caltrans Identified Sensitive Species?[d]
Low	Salamander	Scott Bar Salamander	*Plethodon asupak*	62	62	-	THR		
	Salamander	Dunn's Salamander	*Plethodon dunni*	62	62	-			
	Salamander	Del Norte Salamander	*Plethodon elongatus*	62	62	-			
	Salamander	Siskiyou Mountains Salamander	*Plethodon stormi*	62	62	-	THR		
	Frog	California Treefrog	*Pseudacris cadaverina*	61	61	26			
	Salamander	Southern Torrent Salamander	*Rhyacotriton variegatus*	61	61	5	1		
	Lizard	Peninsula Leaf-toed Gecko	*Phyllodactylus nocticolus*	60	60	-			
	Lizard	Northern Alligator Lizard	*Elgaria coerulea*	60	60	-			
	Frog	Coastal Tailed Frog	*Ascaphus truei*	59	59	30	2		Yes
	Lizard	Common Side-blotched Lizard	*Uta stansburiana*	59	59	-			
	Lizard	Coachella Fringe-toed Lizard	*Uma inornata*	56	56	-	THR		
	Lizard	Colorado Desert Fringe-toed Lizard	*Uma notata*	56	56	-	2		
	Lizard	Mohave Fringe-toed Lizard	*Uma scoparia*	56	56	-	3		
	Frog	Lowland Leopard Frog	*Lithobates yavapaiensis (Possibly extinct in CA)*	54	31	54	1		
	Frog	Southern Mountain Yellow-legged Frog	*Rana muscosa*	54	26	54	END		
	Lizard	Zebra-tailed Lizard	*Callisaurus draconoides*	54	54	-			
	Salamander	Wandering Salamander	*Aneides vagrans*	53	53	-			
	Salamander	Slender Salamanders	*Batrachoseps (genus: 20 spp.)*	53	53	-	END[e]		
Very Low	Salamander	Ensatina	*Ensatina eschscholtzii*	51	51	-			
	Salamander	Yellow-blotched Ensatina	*Ensatina eschscholtzii croceater*	51	51	-			
	Salamander	Large-blotched Ensatina	*Ensatina eschscholtzii klauberi*	51	51	-			
	Lizard	Southern Alligator Lizard	*Elgaria multicarinata*	51	51	-			
	Lizard	Panamint Alligator Lizard	*Elgaria panamintina*	51	51	-	3		
	Frog	Sierra Nevada Yellow-legged Frog	*Rana sierrae*	51	51	36	THR		
	Lizard	Western Fence Lizard	*Sceloporus occidentalis*	49	49	-			
	Salamander	Limestone Salamander	*Hydromantes brunus*	48	48	-	THR		
	Salamander	Mount Lyell Salamander	*Hydromantes platycephalus*	48	48	-			
	Salamander	Clouded Salamander	*Aneides ferreus*	44	44	-			
	Salamander	Arboreal Salamander	*Aneides lugubris*	44	44	-			
	Lizard	Granite Spiny Lizard	*Sceloporus orcutti*	43	43	-			
	Snake	Western Blind Snake	*Rena humilis*	42	42	-			
	Lizard	Desert Spiny Lizard	*Sceloporus magister*	41	41	-			
	Lizard	Common Sagebrush Lizard	*Sceloporus graciosus*	39	41	-			
	Lizard	Gilbert's Skink	*Plestiodon gilberti*	39	39	-			
	Lizard	Western Skink	*Plestiodon skiltonianus*	39	39	-			
	Lizard	California Legless Lizard	*Anniella pulchra*	35	39	-	2		
	Salamander	Black Salamander	*Aneides flavipunctatus*	35	35	-			
	Salamander	Santa Cruz Black Salamander	*Aneides flavipunctatus niger*	35	35	-			
	Lizard	Baja California Collared Lizard	*Crotaphytus vestigium*	35	35	-			
	Lizard	Sandstone Night Lizard	*Xantusia gracilis*	33	33	-	3		
	Lizard	Granite Night Lizard	*Xantusia henshawi*	33	33	-			
	Lizard	Island Night Lizard	*Xantusia riversiana*	33	33	-	THR		
	Lizard	Sierra Night Lizard	*Xantusia sierrae*	33	33	-	1		
	Lizard	Desert Night Lizard	*Xantusia vigilis*	33	33	-			
	Lizard	Wiggins' Night Lizard	*Xantusia wigginsi*	33	33	-			
	Lizard	Long-tailed Brush Lizard	*Urosaurus graciosus*	27	27	-			
	Lizard	Baja California Brush Lizard	*Urosaurus nigricaudus*	27	27	-			
	Lizard	Ornate Tree Lizard	*Urosaurus ornatus*	27	27	-			
	Lizard	Mearns' Rock Lizard	*Petrosaurus mearnsi*	21	21	-			

[a] Maximum scores color-coded for toad risk type; terrestrial (gray), aquatic (blue), or both (gray/blue)
[b] END=Endangered, THR= Threatened, 1-3= ARSSC Priority Ranking
[c] Federal Recovery plans, 5-year reviews, California species accounts for special status species
[d] California Amphibian and Reptile Crossing Preliminary Investigation
[e] 4 Batrachoseps species with conservation status

Table 9 Terrestrial risk ranking and population buffer distances

Risk Level (Terrestrial)		Species			Risk Scores (Terrestrial)		Movement Distances (Terrestrial)		
Species	Population	Group	Common Name	Scientific name	Road Risk: Species- Level	Road Risk: Population-Level	95% Population Movement Distance (m)	Confidence in Distance Estimate	Surrogate Used
Very High	Very High	Snake	San Joaquin Coachwhip	*Masticophis flagellum ruddocki*	689	285	1618	High	*M. fulginosus*
	Very High	Snake	Alameda Striped Racer	*Masticophis lateralis euryxanthus*	652	221	631	Med/High	
	Very High	Tortoise	Mohave Desert Tortoise	*Gopherus agassizii*	580	240	1155	High	
	Very High	Salamander	Red-bellied Newt	*Taricha rivularis*	561	228	1600	High	
	Very High	Snake	Baja California Coachwhip	*Masticophis fuliginosus*	534	285	1904	High	
	Very High	Snake	Coast Patch-nosed Snake	*Salvadora hexalepis virgultea*	533	221	631	Low	*M. lateralis*
	Very High	Salamander	California Newt	*Taricha torosa*	532	228	2500	Med/High	
	Very High	Lizard	Banded Gila Monster	*Heloderma suspectum cinctum*	446	210	1250	High	
	High	Salamander	California Tiger Salamander	*Ambystoma californiense*	437	152	1849	Med/High	
	Very High	Salamander	Sierra Newt	*Taricha sierrae*	437	228	2050	Med	*T. torosa, T. rivularis*
	Very High	Snake	Striped Whipsnake	*Masticophis taeniatus*	425	300	2380	Med	
	Very High	Lizard	Flat-tail Horned Lizard	*Phrynosoma mcallii*	425	217	788	Med/High	
	High	Lizard	Blunt-nosed Leopard Lizard	*Gambelia sila*	393	133	510	High	
	Very High	Snake	Baja California Ratsnake	*Bogertophis rosaliae*	387	238	780	Low	*Elaphe obsoleta*
	Very High	Snake	Panamint Rattlesnake	*Crotalus stephensi*	387	238	938	Med	*C. mitchelli*
	High	Frog	California Red-legged Frog	*Rana draytonii*	380	152	2360	High	
	High	Toad	Yosemite Toad	*Anaxyrus canorus*	379	128	1152	Med/High	
	High	Toad	Black Toad	*Anaxyrus exsul*	379	128	951	Low	*A. canorus, A. punctatus*
	High	Lizard	Cope's Leopard Lizard	*Gambelia copeii*	372	175	643	Low/Med	*G. wislenzii*
	High	Toad	Sonoran Desert Toad	*Incilius alvarius (Possibly extinct in CA)*	361	152	1400	Low/Med	*A. cognatus*
	Very High	Lizard	Desert Horned Lizard	*Phrynosoma platyrhinos*	356	259	1308	Med/High	
	High	Snake	California Glossy Snake	*Arizona elegans occidentalis*	340	154	316	Low	*R. lecontii*
	Very High	Snake	North American Racer	*Coluber constrictor*	334	308	1800	Med	
	Very High	Snake	Coachwhip	*Masticophis flagellum*	333	285	1618	High	*M. fulginosus*
	High	Toad	Arroyo Toad	*Anaxyrus californicus*	331	128	1082	Med/High	
	Very High	Snake	Striped Racer	*Masticophis lateralis*	322	221	631	Med	
High	High	Snake	Red Diamond Rattlesnake	*Crotalus ruber*	321	175	853	High	
	Very High	Snake	Speckled Rattlesnake	*Crotalus mitchellii*	317	238	938	High	
	Med	Salamander	Santa Cruz Long-toed Salamander	*Ambystoma macrodactylum croceum*	308	104	700	High	
	Very High	Salamander	Rough-skinned Newt	*Taricha granulosa*	304	228	2050	Med	*T. torosa, T. rivularis*
	High	Snake	Regal Ring-necked Snake	*Diadophis punctatus regalis*	298	152	566	Low/Med	
	Very High	Snake	California Lyresnake	*Trimorphodon lyrophanes*	293	195	800	Low	
	High	Frog	Northern Red-legged Frog	*Rana aurora*	291	152	2360	Med	*R. draytonii*
	High	Turtle	Southern Western Pond Turtle	*Actinemys pallida*	283	128	309	Med-High	
	High	Snake	Mojave Rattlesnake	*Crotalus scutulatus*	276	189	815	Med/High	
	Very High	Snake	Western Patch-nosed Snake	*Salvadora hexalepis*	276	221	631	Low	*M. lateralis*
	High	Snake	Sidewinder	*Crotalus cerastes*	263	186	767	High	
	Med	Salamander	California Giant Salamander	*Dicamptodon ensatus*	260	120	600	Low	*D. tenebrosus*
	Very High	Snake	Sonoran Lyresnake	*Trimorphodon lambda*	260	195	800	Low	
	Very High	Snake	Western Rattlesnake	*Crotalus oreganus*	250	231	1096	Med/High	
	High	Snake	Desert Nightsnake	*Hypsiglena chlorophaea*	241	175	566	Low	*D. punctatus*
	Med	Snake	San Francisco Gartersnake	*Thamnophis sirtalis tetrataenia*	238	81	300	Med	
	Med	Lizard	Switak's Banded Gecko	*Coleonyx switaki*	236	90	200	Low	*C. variegatus (AZ)*
	Med	Toad	Western Spadefoot	*Spea hammondii*	234	104	670	Med	
	High	Snake	Coast Nightsnake	*Hypsiglena ochrorhyncha*	233	175	566	Low	*D. punctatus*
	High	Lizard	Long-nosed Leopard Lizard	*Gambelia wislizenii*	226	175	643	Med/High	
	High	Toad	Great Plains Toad	*Anaxyrus cognatus*	222	152	1400	Med/High	
	High	Toad	Woodhouse's Toad	*Anaxyrus woodhousii*	222	152	1400	Low	*A. cognatus*
	Med	Lizard	Coastal Whiptail	*Aspidoscelis tigris stejnegeri*	219	105	300	Low	*A. hyperythra (multiplied by 2 for body size)*
	High	Turtle	Northern Western Pond Turtle	*Actinemys marmorata*	219	128	448	Med	
	High	Snake	Western Shovel-nosed Snake	*Chionactis occipitalis*	218	154	400	Low	
	High	Snake	Spotted Leaf-nosed Snake	*Phyllorhynchus decurtatus*	218	154	400	Low	*C. occipitalis, M. taeniatus*
	Med	Salamander	Southern Long-toed Salamander	*Ambystoma macrodactylum sigillatum*	217	104	700	Med	
	Med	Frog	Cascades Frog	*Rana cascadae*	217	104	759	High	
	High	Snake	Western Diamond-backed Rattlesnake	*Crotalus atrox*	214	147	484	Med	
	High	Snake	Western Groundsnake	*Sonora semiannulata*	212	154	400	Low	*C. occipitalis*
	Med	Snake	California Red-sided Gartersnake	*Thamnophis sirtalis infernalis*	211	81	300	Low/Med	*T.s. tetrataenia*

Table 9 continued

Risk Level (Terrestrial)		Species			Risk Scores (Terrestrial)		Movement Distances (Terrestrial)		
Species	Population	Group	Common Name	Scientific name	Road Risk: Species- Level	Road Risk: Population-Level	95% Population Movement Distance (m)	Confidence in Distance Estimate	Surrogate Used
Medium	Med	Lizard	Blainville's Horned Lizard	*Phrynosoma blainvillii*	209	114	495	Med	
	Med	Snake	Two-striped Gartersnake	*Thamnophis hammondii*	195	81	239	Low/Med	
	High	Snake	Gopher Snake	*Pituophis catenifer*	189	189	820	Med/High	
	High	Snake	California Mountain Kingsnake	*Lampropeltis zonata*	184	147	501	Low/Med	*L. getula, L. triangulum*
	High	Snake	Glossy Snake	*Arizona elegans*	180	154	316	Low	*R. lecontii*
	Med	Lizard	Pygmy Short-horned Lizard	*Phrynosoma douglasii*	179	123	400	Low	*P. mccallii (reduced 0.5 for body size)*
	Med	Toad	Couch's Spadefoot	*Scaphiopus couchii*	178	104	670	Med	
	High	Snake	California Kingsnake	*Lampropeltis californiae*	175	175	501	Med/High	
	High	Snake	Long-nosed Snake	*Rhinocheilus lecontei*	165	132	337	Low/Med	
	High	Snake	Common Gartersnake	*Thamnophis sirtalis*	165	137	532	Low/Med	
	High	Toad	Western Toad	*Anaxyrus boreas*	165	152	2144	Med/High	
	High	Snake	Ring-necked Snake	*Diadophis punctatus*	164	136	566	Low/Med	
	Med	Lizard	San Diego Banded Gecko	*Coleonyx variegatus abbotti*	158	84	200	Low/Med	*C. variegatus (AZ)*
	Med	Salamander	Northwestern Salamander	*Ambystoma gracile*	152	104	700	Low	*A. macrodactylum croceum*
	Med	Toad	Great Basin Spadefoot	*Spea intermontana*	152	104	670	Med	
	Med	Toad	Red-spotted Toad	*Anaxyrus punctatus*	147	104	750	Low	
	Med	Salamander	Long-toed Salamander	*Ambystoma macrodactylum*	143	104	700	Med	
	Med	Snake	Northwestern Gartersnake	*Thamnophis ordinoides*	138	95	239	Low	*T. hammondii*
	Med	Lizard	Orange-throated Whiptail	*Aspidoscelis hyperythra*	137	84	150	Low/Med	
	Med	Snake	Smith's Black-headed Snake	*Tantilla hobartsmithi*	136	105	150	Low	
	Med	Snake	California Black-headed Snake	*Tantilla planiceps*	133	84	150	Low	
	Med	Lizard	Western Whiptail	*Aspidoscelis tigris*	118	105	300	Low	*A. hyperythra (multiplied by 2 for body size)*
	Med	Salamander	Coastal Giant Salamander	*Dicamptodon tenebrosus*	117	80	600	Low/Med	
	Med	Lizard	Western Banded Gecko	*Coleonyx variegatus*	105	84	200	Low/Med	*C. variegatus (AZ)*
	Med	Lizard	Common Chuckwalla	*Sauromalus ater*	78	78	296	Med	
	Med	Snake	Northern Rubber Boa	*Charina bottae*	77	77	230	Low/Med	*L. trivirgata*
	Med	Snake	Southern Rubber Boa	*Charina umbratica*	77	77	230	Low/Med	*L. trivirgata*
	Med	Snake	Northern Three-lined Boa	*Lichanura orcutti*	77	77	230	Med/High	
	Med	Snake	Western Terrestrial Gartersnake	*Thamnophis elegans*	75	75	104	Low/Med	*T.gigas (-40% for size diff)*
	Med	Lizard	Desert Iguana	*Dipsosaurus dorsalis*	72	72	150	Low/Med	
	Med	Snake	Forest Sharp-tailed Snake	*Contia longicauda*	70	70	150	Low	
	Med	Snake	Common Sharp-tailed Snake	*Contia tenuis*	70	70	150	Low	
	Med	Snake	Checkered Gartersnake	*Thamnophis marcianus*	69	69	239	Low	*T. hammondii*
	Med	Frog	Pacific Treefrog	*Pseudacris regilla*	68	68	400	Low/Med	
Low	Low	Salamander	Scott Bar Salamander	*Plethodon asupak*	62	62	92	Low	*P. glutinosus*
	Low	Salamander	Dunn's Salamander	*Plethodon dunni*	62	62	92	Low	*P. glutinosus*
	Low	Salamander	Del Norte Salamander	*Plethodon elongatus*	62	62	92	Low	*P. glutinosus*
	Low	Salamander	Siskiyou Mountains Salamander	*Plethodon stormi*	62	62	92	Low	*P. glutinosus*
	Low	Frog	California Treefrog	*Pseudacris cadaverina*	61	61	50	Low/Med	
	Low	Salamander	Southern Torrent Salamander	*Rhyacotriton variegatus*	61	61	50	Low	*R. cascadae*
	Low	Lizard	Peninsula Leaf-toed Gecko	*Phyllodactylus nocticolus*	60	60	200	Low	*C. variegatus (AZ)*
	Low	Lizard	Northern Alligator Lizard	*Elgaria coerulea*	60	60	106	Med	
	Low	Frog	Coastal Tailed Frog	*Ascaphus truei*	59	59	150	Med/High	
	Low	Lizard	Common Side-blotched Lizard	*Uta stansburiana*	59	59	152	Med/High	
	Low	Lizard	Coachella Fringe-toed Lizard	*Uma inornata*	56	56	52	Med/High	
	Low	Lizard	Colorado Desert Fringe-toed Lizard	*Uma notata*	56	56	75	Med/High	
	Low	Lizard	Mohave Fringe-toed Lizard	*Uma scoparia*	56	56	64	Med	*U. notata, U. inornata*
	Low	Lizard	Zebra-tailed Lizard	*Callisaurus draconoides*	54	54	150	Med	
	Low	Salamander	Wandering Salamander	*Aneides vagrans*	53	53	39	Med/High	
	Low	Salamander	Slender Salamanders (20 species)	*Batrachoseps (genus)*	53	53	50	Low/Med	*B. pacificus*

Table 9 continued

Risk Level (Terrestrial)		Species			Risk Scores (Terrestrial)		Movement Distances (Terrestrial)		
Species	Population	Group	Common Name	Scientific name	Road Risk: Species- Level	Road Risk: Population-Level	95% Population Movement Distance (m)	Confidence in Distance Estimate	Surrogate Used
Very Low	Very Low	Salamander	Ensatina	*Ensatina eschscholtzii*	51	51	75	Med	
	Very Low	Salamander	Yellow-blotched Ensatina	*Ensatina eschscholtzii croceater*	51	51	75	Med	
	Very Low	Salamander	Large-blotched Ensatina	*Ensatina eschscholtzii klauberi*	51	51	75	Med	*E. eschscholtzii croceater*
	Very Low	Lizard	Southern Alligator Lizard	*Elgaria multicarinata*	51	51	106	Low/Med	*E. coerulea*
	Very Low	Lizard	Panamint Alligator Lizard	*Elgaria panamintina*	51	51	106	Low/Med	*E. coerulea*
	Very Low	Frog	Sierra Nevada Yellow-legged Frog	*Rana sierrae*	51	51	420	Med	
	Very Low	Lizard	Western Fence Lizard	*Sceloporus occidentais*	49	49	160	Med	
	Very Low	Salamander	Limestone Salamander	*Hydromantes brunus*	48	48	80	Low	
	Very Low	Salamander	Mount Lyell Salamander	*Hydromantes platycephalus*	48	48	80	Low	
	Very Low	Salamander	Clouded Salamander	*Aneides ferreus*	44	44	39	Med	*A. vagrans*
	Very Low	Salamander	Arboreal Salamander	*Aneides lugubris*	44	44	39	Med	*A. vagrans*
	Very Low	Snake	Giant Gartersnake	*Thamnophis gigas*	44	44	174	High	
	Very Low	Snake	Sierra Gartersnake	*Thamnophis couchii*	44	44	115	Low/Med	*T.gigas (-34% for size diff)*
	Very Low	Lizard	Granite Spiny Lizard	*Sceloporus orcutti*	43	43	91	Low/Med	
	Very Low	Snake	Western Blind Snake	*Rena humilis*	42	42	50	Low	
	Very Low	Lizard	Desert Spiny Lizard	*Sceloporus magister*	41	41	91	Low	
	Very Low	Frog	Oregon Spotted Frog	*Rana pretiosa (Possibly extinct in CA)*	41	41	100	Low	
	Very Low	Lizard	Common Sagebrush Lizard	*Sceloporus graciosus*	41	41	41	Med/High	
	Very Low	Snake	Aquatic Gartersnake	*Thamnophis atratus*	40	40	99	Low/Med	*T.gigas (-43% for size diff)*
	Very Low	Lizard	Gilbert's Skink	*Plestiodon gilberti*	39	39	93	Low/Med	*P. skiltonianus, P. fasciatus, S. laterale*
	Very Low	Lizard	Western Skink	*Plestiodon skiltonianus*	39	39	93	Low/Med	
	Very Low	Lizard	California Legless Lizard	*Anniella pulchra*	39	39	15	High	
	Very Low	Turtle	Sonoran Mud Turtle	*Kinosternon sonoriense*	37	37	60	Med	
	Very Low	Salamander	Black Salamander	*Aneides flavipunctatus*	35	35	39	Med	*A. vagrans*
	Very Low	Salamander	Santa Cruz Black Salamander	*Aneides flavipunctatus niger*	35	35	39	Med	*A. vagrans*
	Very Low	Lizard	Great Basin Collared Lizard	*Crotaphytus bicinctores*	35	35	150	Low/Med	*C. collaris*
	Very Low	Lizard	Baja California Collared Lizard	*Crotaphytus vestigium*	35	35	150	Low/Med	*C. collaris*
	Very Low	Lizard	Sandstone Night Lizard	*Xantusia gracilis*	33	33	14	Med/High	*X. riversiana*
	Very Low	Lizard	Granite Night Lizard	*Xantusia henshawi*	33	33	14	Med/High	*X. riversiana*
	Very Low	Lizard	Island Night Lizard	*Xantusia riversiana*	33	33	14	High	
	Very Low	Lizard	Sierra Night Lizard	*Xantusia sierrae*	33	33	14	Med/High	*X. riversiana*
	Very Low	Lizard	Desert Night Lizard	*Xantusia vigilis*	33	33	14	Med/High	*X. riversiana*
	Very Low	Lizard	Wiggins' Night Lizard	*Xantusia wigginsi*	33	33	14	Med/High	*X. riversiana*
	Very Low	Frog	Lowland Leopard Frog	*Lithobates yavapaiensis (Possibly extinct in CA)*	31	31	100	Low	
	Very Low	Lizard	Long-tailed Brush Lizard	*Urosaurus graciosus*	27	27	130	Low/Med	*S. occidentalis, S. graciosus*
	Very Low	Lizard	Baja California Brush Lizard	*Urosaurus nigricaudus*	27	27	130	Low/Med	*S. occidentalis, S. graciosus*
	Very Low	Lizard	Ornate Tree Lizard	*Urosaurus ornatus*	27	27	130	Low/Med	*S. occidentalis, S. graciosus*
	Very Low	Frog	Foothill Yellow-legged Frog	*Rana boylii*	26	26	40	Med/High	
	Very Low	Frog	Southern Mountain Yellow-legged Frog	*Rana muscosa*	26	26	40	Med	*R. boylii*
	Very Low	Lizard	Mearns' Rock Lizard	*Petrosaurus mearnsi*	21	21	80	Low/Med	
	Very Low	Lizard	Mearns' Rock Lizard	*Petrosaurus mearnsi*	21	21	80	Low/Med	

over the surface during high flow events. These may be used as road crossings by species traveling along ephemeral stream corridors with or without water flow. Given these potential vulnerabilities, we believe that road impacts to aquatic connectivity of herpetofauna deserve greater consideration.

Across broad taxonomic groups, chelonids (tortoises/turtles) and snakes had the greatest percentages of species at 'high' or 'very high' risk from roads. They are similar in that many move long distances (home range and/or migratory), tend not to avoid roads (or are attracted to them for thermoregulation), are long lived, and have relatively low fecundity in comparison to other herpetofaunal groups. Because of these traits, chelonids and snakes have been identified elsewhere as being particularly susceptible to negative population effects from roads (Gibbs and Shriver 2002; Andrews et al. 2015b; Jackson et al. 2015).

There are only four species of chelonids in California, (desert tortoise (*Gopherus agazzii*), Northwestern pond turtle (*Actinemys marmorata*), Southwestern pond turtle (*Actinemys pallida*), and the Sonoran mud turtle (*Kinosternon sonoriense*)). There has been a high level of attention to road impacts on the desert tortoise (*Gopherus agazzii*) as numerous studies have documented not only high road mortality, but measurable road effect zones, and mostly positive responses to barriers and underpasses (e.g., Boarman and Sazaki 1996, 2006; Peaden et al. 2016; but see Peadon et al. 2017). Although not listed as a primary threat to pond turtle populations in California (Thomson et al. 2016), road mortality is a major concern for western pond turtle populations in Oregon (Rosenberg et al. 2009). Pond turtles travel kilometers within perennial waters and from pool to pool in intermittent aquatic habitats to forage and find mates (Goodman and Stewart 2000). In addition, females nest and lay eggs in terrestrial habitats up to 0.5 km away from water which make roads that parallel aquatic habitat a threat to both females and hatchlings (Reese and Welsh 1997; Rathbun et al. 2002; Pilliod et al. 2013). In fact, road mortality of females has been identified as a cause for male-biased sex ratios in some populations of pond turtles and other freshwater turtle species (Steen et al. 2006; Rosenberg et al. 2009; Reid and Peery 2014). Therefore, this species requires consideration of both aquatic and terrestrial connectivity to satisfy their annual resource requirements. Sonoran mud turtles also travel long distances within intermittent streams and thus may be at risk of roads that transect their aquatic habitat (Hensley et al. 2010).

Larger colubrid snakes (Family Colubridae; many genera) and rattlesnakes (genus *Crotalus*) were ranked among the highest risk from negative road effects. In addition to being attracted to paved road surfaces for thermoregulation, many large snakes have wide home-ranges or may move large distances between winter hibernacula and summer foraging areas. In contrast to smaller species, larger snakes are also less likely to avoid roads (Rosen and Lowe 1994; Andrews and Gibbons 2005; Andrews et al. 2008; Siers et al. 2016). High road mortality (e.g., Klauber 1931; Rosen and Lowe 1994; Jones et al. 2011), reduced abundance near roads (Rudolph et al. 1999; Jones et al. 2011), increased extinction risk (Row et al. 2007), and decreased genetic diversity (Clark et al. 2010; Hermann et al. 2017) have been documented for numerous snake species; as have positive responses to barriers and underpasses (Dodd et al. 2004; Colley et al. 2017). In our statewide risk analysis, coachwhips (genus *Masticophis/Coluber*) were amongst the highest risk groups at both the population and species-levels. These are particularly wide-ranging and very active foragers in comparison to other snake genera (Stebbins and McGinnis 2012). The coachwhip (*Masticophis flagellum)* was found to be ninefold more likely to be extirpated from habitats that were fragmented by roads and urbanization, contributing to their decline throughout California (Case and Fisher 2001; Mitrovich 2006). Similarly, habitat fragmentation from roads and urbanization were identified as primary threats to the Alameda whipsnake (*Masticophis lateralis euryxanthus* USFWS 2011). Although road use and mortality have been documented for many other terrestrial California snake species on road-riding surveys (e.g., Klauber 1931; Jones et al. 2011; Shilling and Waetjen 2017), there is a paucity of studies examining population-level effects of roads on California snake species. We could find only one such study, where presence of a highway was shown to reduce gene flow in the Western diamond-backed rattlesnake (*Crotalus atrox)* in the Sonoran Desert, AZ (Hermann et al. 2017).

Long foraging movements within aquatic habitats also contributed to the majority of garter snakes (genus: *Thamnophis*) falling within the highest road risk categories. Maintaining aquatic and wetland connectivity is of primary concern for these species. Garter snakes also use terrestrial habitats for overwintering, reproduction, and for moving among wetland or aquatic patches. Some migrate long distances to winter hibernacula, making them also susceptible to roads within adjacent terrestrial habitats (Roe et al. 2006; Jackson et al. 2015). The highly aquatic giant garter snake (*Thamnophis gigas*) had the highest aquatic road risk score. Because it moves only short distances on land (Halstead et al. 2015), mitigation may best focus on functional aquatic passages with lengths of adjacent road barriers based upon their terrestrial movement distances.

Toads were the third highest ranking group with 64% ranked in the highest risk categories. In particular, Bufonid toads (family Bufonidae) may move large distances (> 1 km) in both aquatic and terrestrial habitats to satisfy their annual resource requirements; thus 5 of 7 bufonid species ranked high or very high risk from roads. Consistent with our risk assessment

Table 10 Aquatic risk ranking and population buffer distances

Risk Level (Aquatic)		Species			Risk Scores (Aquatic)		Movement Distances (Aquatic)		
Species	Population	Group	Common Name	Scientific name	Road Risk: Species- Level	Road Risk: Population-Level	95% Population Movement Distance (m)	Confidence in Distance Estimate	Surrogate Used
Very High	Very High	Snake	Giant Gartersnake	*Thamnophis gigas*	710	240	1556	Med/High	
	Very High	Turtle	Southern Western Pond Turtle	*Actinemys pallida*	707	320	3145	High	
	Very High	Snake	San Francisco Gartersnake	*Thamnophis sirtalis tetrataenia*	663	224	1146	Med	*T. sirtalis*
	Very High	Snake	California Red-sided Gartersnake	*Thamnophis sirtalis infernalis*	588	224	1146	Med	*T. sirtalis*
	Very High	Turtle	Northern Western Pond Turtle	*Actinemys marmorata*	547	320	3145	High	*A. pallida*
	Very High	Snake	Two-striped Gartersnake	*Thamnophis hammondii*	541	224	979	Low	*T.gigas (-37% for size diff)*
	High	Turtle	Sonoran Mud Turtle	*Kinosternon sonoriense*	399	168	1000	Med	
High	Med	Frog	Oregon Spotted Frog	*Rana pretiosa (Possibly extinct in CA)*	315	120	1300	Low	
	Very High	Snake	Sierra Gartersnake	*Thamnophis couchii*	304	192	1021	Low	*T.gigas (-34% for size diff)*
	Med	Frog	California Red-legged Frog	*Rana draytonii*	300	120	1864	High	
	Med	Toad	Sonoran Desert Toad	*Incilius alvarius (Possibly extinct in CA)*	285	120	1400	Low/Med	*A. cognatus*
	Med	Toad	Yosemite Toad	*Anaxyrus canorus*	284	96	1152	Med/High	
	Med	Toad	Black Toad	*Anaxyrus exsul*	284	96	951	Low/Med	*A. canorus, A. punctatus*
	Very High	Snake	Common Gartersnake	*Thamnophis sirtalis*	271	224	1146	Med	
	High	Snake	Aquatic Gartersnake	*Thamnophis atratus*	266	168	889	Low	*T.gigas (-43% for size diff)*
	Med	Toad	Arroyo Toad	*Anaxyrus californicus*	248	96	1000	Med/High	
	High	Snake	Northwestern Gartersnake	*Thamnophis ordinoides*	245	168	775	Low	*T.gigas (-50% for size diff)*
	Very High	Snake	Western Terrestrial Gartersnake	*Thamnophis elegans*	240	192	931	Low	*T.gigas (-40% for size diff)*
	Med	Frog	Northern Red-legged Frog	*Rana aurora*	230	120	1864	Med	*R. draytonii*
Medium	High	Snake	Checkered Gartersnake	*Thamnophis marcianus*	210	144	835	Low	*T.gigas (-46% for size diff)*
	Med	Frog	Foothill Yellow-legged Frog	*Rana boylii*	199	90	2420	Med/High	
	Med	Toad	Great Plains Toad	*Anaxyrus cognatus*	175	120	1400	Med/High	
	Med	Toad	Woodhouse's Toad	*Anaxyrus woodhousii*	175	120	1400	Low/Med	*A. cognatus*
	Med	Toad	Western Toad	*Anaxyrus boreas*	130	120	1274	Low/Med	
	Med	Salamander	Red-bellied Newt	*Taricha rivularis*	72	72	600	High	
	Med	Salamander	California Newt	*Taricha torosa*	72	72	600	Med/High	*T. rivularis*
	Med	Salamander	Sierra Newt	*Taricha sierrae*	72	72	600	Med	*T. rivularis*
	Med	Salamander	Rough-skinned Newt	*Taricha granulosa*	72	72	600	Med	*T. rivularis*
	Med	Salamander	California Giant Salamander	*Dicamptodon ensatus*	72	72	600	Low	*Educated guess*
	Med	Frog	Cascades Frog	*Rana cascadae*	72	72	759	High	
	Med	Toad	Red-spotted Toad	*Anaxyrus punctatus*	72	72	750	Med	
Low	Low	Frog	Lowland Leopard Frog	*Lithobates yavapaiensis (Possibly extinct in CA)*	54	54	900	Low	
	Low	Frog	Southern Mountain Yellow-legged Frog	*Rana muscosa*	54	54	665	Med	
Very Low	Very Low	Salamander	Coastal Giant Salamander	*Dicamptodon tenebrosus*	48	48	600	Low	*Educated guess*
	Very Low	Frog	Pacific Treefrog	*Pseudacris regilla*	36	36	400	Low	*Educated guess*
	Very Low	Frog	Sierra Nevada Yellow-legged Frog	*Rana sierrae*	36	36	525	Med/High	
	Very Low	Frog	Coastal Tailed Frog	*Ascaphus truei*	30	30	266	Med/High	
	Very Low	Frog	California Treefrog	*Pseudacris cadaverina*	26	26	200	Low/Med	
	Very Low	Salamander	Southern Torrent Salamander	*Rhyacotriton variegatus*	5	5	50	Low/Med	*R. cascadae*

results, there is evidence that bufonid toads are particularly susceptible to negative impacts from roads elsewhere (Trenham et al. 2003; Orłowski 2007; Eigenbrod et al. 2008).

Roads and traffic have been associated with reduced abundance and species richness of frog populations (e.g., Fahrig et al. 1995; Houlahan and Findlay 2003). However, approximately half of California species are small, primarily aquatic, highly fecund, with relatively limited movements and thus ranked low for road impacts. Four of 11 species ranked within the highest risk groupings; California red-legged frog (*Rana draytonii*), Oregon spotted frog (*R. pretiosa*), Northern red-legged frog (*R. aurora*), and Cascades frog (*R. cascadae*). The Oregon spotted frog (*R. pretiosa*) is known to move large distances within aquatic habitats (Bourque 2008; USFWS 2009). Construction of a highway that bisected the

Yellowstone population of Oregon spotted frogs was one important factor that reduced the population dramatically in the 1950s (see discussion in Watson et al. 2003). Although portions of the populations show high site fidelity, California red-legged frog and Northern red-legged frog migrants can move large distances (> 1 km) across both aquatic and terrestrial habitats (Bulger et al. 2003; Fellers and Kleeman 2007; Hayes et al. 2007). Road mortality or habitat fragmentation from roads and urbanization were listed as primary threats to these species elsewhere (USFWS 2002; COSEWIC 2015).

Lizards had relatively low percentages of species in the high risk groupings. Many lizard species are small, non-migratory, territorial, have small home ranges and are thus at low risk of negative road effects. Similar to snakes, lizards can also be attracted to road surfaces for thermoregulation. A few wide ranging species scored in the highest risk categories including the Gila monster (*Heloderma suspectum*), leopard lizards (genus *Gambelia*) and two horned lizard species (genus *Phrynosoma*). The Gila monster has been negatively associated with urbanization, where larger home ranges and greater movement rates result in higher mortality for males (Kwiatkowski et al. 2008). Sensitive to habitat fragmentation, the blunt-nosed leopard lizard (*Gambelia sila*) was found to be largely absent from habitat patches less than 250 ha (Bailey and Germano 2015). Flat-tailed horned lizards (*Phrynosoma mccallii*) are also susceptible to habitat fragmentation with very large home ranges for their size, particularly in wet years (Young and Young 2000). In fact, road mortality is a well-known threat for this species (see review by CDFW 2016b). Horned lizards are also particularly vulnerable to being killed on roads due to their tendency to flatten and remain motionless while being approached (Young and Young 2000).

Salamanders also had relatively low percentages of species in the high risk grouping. Over 75% (35/46) of the California salamanders are lungless salamanders (Plethodontidae) and Torrent salamanders (Rhyacotritonidae). These species are mostly small, sedentary, non-migratory, closed habitat specialists with limited movement distances and these traits have resulted in a high level of speciation. This is exemplified by there being at least 20 species of slender salamanders (genus *Batrachoseps*) in California alone (Martinez-Solano et al. 2007; Vences and Wake 2007). However, within the salamander group, newts and several other migratory salamander species were ranked within the highest risk categories from negative road effects. There is substantial evidence that habitat fragmentation and mortality due to roads negatively affect many of these species. For instance, newts regularly migrate long distances over land from and to breeding ponds, and to terrestrial foraging habitats (> 2 km; Trenham 1998). Large numbers are found dead on roads during dispersal periods and newt species are often the first to disappear in fragmented landscapes (Gibbs 1998; Trenham 1998, Shields pers. comm.). Similarly, road mortality and habitat fragmentation are primary threats to the California tiger salamander and other Ambystomid salamanders because terrestrial habitat is used for interpond migration and overwintering (Semlitsch 1998; Trenham et al. 2001; Bolster 2010).

Because this assessment covers a wide array of species and habitats, the risk to particular species populations must be re-assessed on a local level. This includes consideration of the locations, types, and densities of roads in relation to population and species ranges along with goals for functional, meta-population, and genetic connectivity (e.g., Marsh and Jaeger 2015). Due to very low road densities in their limited ranges, some species and populations may be at lower risk. For instance the Gila monster, Oregon spotted frog, Sonoran mud turtle, Sonoran desert toad (*Incilius alvarius*) and Yosemite toad (*Anaxyrus canorus*) scored high due to life history and space-use characteristics, however their limited ranges are largely in protected or low road density areas in the state. Thus roads may not be a significant threat to these species in California. In contrast, high road densities may increase the risk for species within coastal regions such as remaining populations of Santa Cruz long-toed salamander (*Ambystoma macrodactylum croceum*), Alameda striped racer (*Masticophis lateralis euryxanthus*), and San Francisco garter snake (*Thamnophis sirtalis tetrataenia*). However, most species consist of numerous populations with a myriad of differing road-related threat levels. Although detailed species ranges and occupancy within ranges are well known for some species with very limited ranges, for most species range-wide surveys have not been conducted. Therefore, only general range boundaries are available that encompass large portions of the state and availability of species distribution models of habitat suitability and occupancy within their ranges is rare. This lack of detailed spatial information on species distribution further limits the potential to incorporate road locations, types, and densities in a state and species-wide assessment.

We also note that relative risk to negative road impacts is provided for both populations and species. Risk was elevated for species with small and isolated ranges and that are facing a myriad of other threats. Because of this, a few common widespread species scored high at the population-level but not at the species-level. This included gopher snakes (*Pituophis catenifer*) and western toads (*Anaxyrus boreas*) where road mortality has been identified as a threat to the persistence of local populations (e.g., COSEWIC 2012; Jochimsen et al. 2014).

To potentially aid in local assessments, we have provided distance estimates or "buffer zones" that contain estimates for 95% of population-level movements for all species (e.g., Semlitsch and Bodie 2003). We provide all references evaluated for distance estimates in Appendix 2. Meta-population movements can be very important to the stability of pond-breeding amphibians (e.g., Semlitsch 2008; Jackson et al. 2015) and are included in many of the buffer zone calculations. However, we note that buffer zones may not include meta-population-level movements if the rate of these dispersal movements was less than 5% in the studies we used for our analyses.

This should be considered an initial assessment of susceptibility to negative road impacts in a hierarchical framework (e.g., see Level 2; Hobday et al. 2011). Therefore, as previously stated it will be important to re-assess the risk of specific populations to roads within their habitat and to evaluate and compare alternatives at the local scale (e.g., Suter 2016). This may include more detailed information on specific road attributes (e.g., density, type, location), as well as species behavior (Jaeger et al. 2005; Rouse et al. 2011; Rytwinski and Fahrig 2013; Jacobson et al. 2016). Age structured and spatially explicit population viability models are valuable tools to predict long-term population responses to roads and to compare outcomes of multiple mitigation scenarios (e.g., Gibbs and Shriver 2005; Borda-de-Água et al. 2014; Polak et al. 2014; Crawford 2015). Need and placement of mitigation structures can be guided by local population or meta-population dynamics, landscape attributes, movement routes, and road mortality hot spots (e.g., Bissonette and Adair 2008; Langen et al. 2009, 2015b; D'Amico et al. 2016; Loraamm and Downs 2016).

The quantity and quality of life history information, particularly movement data, are highly variable among species (see confidence levels; Tables 9 and 10). Therefore it is important to re-assess risk as new information becomes available. Finally, this is a structured assessment of comparative risk across a range of target species; therefore specific values for high risk have not been established. The ranking or assessment methodology should be adaptive and updated with advancements of road ecology science (e.g., Linkov et al. 2006).

Conclusion

Although roads are a significant cause of mortality and habitat fragmentation for many wildlife populations, road-related risk rankings have been based largely on expert opinion due to a scarcity of literature on road effects for most species. Therefore, we developed an objective and scientifically-based comparative risk approach to assess the potential threat from negative road impacts using species life history and movement data. After applying it to over 160 herpetofaunal species (and subspecies) in the state of California, the results are consistent with road ecology literature in identifying known high risk species, and call attention to some species not previously identified. Overall, we found that snakes and chelonids had the largest proportion of species at high risk for negative road impacts due to longer movement distances (home range and/or migratory), lack of road avoidance, and relatively low fecundity in comparison to other herpetofaunal groups. Results also indicated that consideration of aquatic connectivity appears to be under-represented for semi-aquatic herpetofauna that use both terrestrial and stream, riverine, or wetland habitats.

In addition to informing transportation planning and mitigation considerations for California herpetofauna, we believe this approach may be useful for comparing the risk of road-related fragmentation and mortality for species elsewhere and for other taxonomic groups. The results can help to inform multi-criteria threat assessments for special status species or those in consideration for listing. Finally, this serves to highlight species that may deserve further study and consideration for aquatic and terrestrial road mitigation to reduce mortality and to maintain population-level connectivity.

This risk assessment approach compares the susceptibility of species to negative road impacts. Commonly, there are numerous populations within a species range that occupy areas with greatly differing road pressures. Therefore, the actual risk to specific species populations will depend upon local road densities, road-types, traffic, and road locations in relation to species habitat and movement corridors.

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References

Andrews KM, Gibbons JW (2005) How do highways influence snake movement? Behavioral responses to roads and vehicles. Copeia 4:772–782

Andrews KM, Gibbons JW, Jochimsen D, Mitchell J (2008) Ecological effects of roads on amphibians and reptiles: a literature review. In: Mitchell JC, Jung Brown RE, Bartholomew B (eds) Urban Herpetology, Herpetological Conservation 3. Society for the Study of Reptiles and Amphibians, Salt-Lake City, UT, pp 121–143

Andrews KM, Nanjappa P, Riley SP (eds) (2015a) Roads and ecological infrastructure: concepts and applications for small animals. JHU Press, Baltimore, MD

Andrews KM, Langen TA, Struijk RPJH (2015b) Reptiles: Overlooked but often at risk from roads. Handbook of Road Ecology. Wiley, New York, pp 271–280

Bailey CV, Germano DJ (2015) Probability of occupancy of blunt-nosed leopard lizards on habitat patches of various sizes in the San Joaquin Desert of California. W Wild 2:23–28

Bissonette JA, Adair W (2008) Restoring habitat permeability to roaded landscapes with isometrically-scaled wildlife crossings. Biol Conserv 141(2):482–488

Boarman WI, Sazaki M (1996) Highway mortality in desert tortoises and small vertebrates: success of barrier fences and culverts (No. FHWA-PD-96-041)

Boarman WI, Sazaki M (2006) A highway's road-effect zone for desert tortoises (*Gopherus agassizii*). J Arid Environ 65(1):94–101

Bolster BC (2010) A status review of the California tiger salamander (*Ambystoma californiense).* Report to the Fish and Game Commission, State of California. Nongame Wildlife Program Report 2010–4

Bonnet X, Naulleau G, Shine R (1999) The dangers of leaving home: dispersal and mortality in snakes. Biol Conserv 89(1):39–50

Borda-de-Água L, Grilo C, Pereira HM (2014) Modeling the impact of road mortality on barn owl (*Tyto alba*) populations using age-structured models. Ecol Model 276:29–37

Bourque R (2008) [North Coast] spatial ecology of an inland population of the foothill yellow-legged frog (*Rana boylii*) in Tehama County, California. Masters Thesis, California State University, Humboldt, pp 107

Brehme CS, Tracey JA, McClenaghan LR, Fisher RN (2013) Permeability of roads to movement of scrubland lizards and small mammals. Conserv Biol 27(4):710–720

Bulger JB, Scott NJ, Seymour RB (2003) Terrestrial activity and conservation of adult California red-legged frogs *Rana aurora draytonii* in coastal forests and grasslands. Biol Conserv 110(1):85–95

California Department of Fish and Wildlife (CDFW) (2016a) Threatened and endangered species. http://www.dfg.ca.gov/wildlife/nongame/t_e_spp/ (accessed August 2016)

California Department of Fish and Wildlife (CDFW) (2016b) A status review of the flat-tailed horned lizard (*Phrynosoma mcallii*) in California. Report to the Fish and Game Commission

Carr LW, Fahrig L (2001) Effect of road traffic on two amphibian species of differing vagility. Conserv Biol 15(4):1071–1078

Case TJ, Fisher RN (2001) Measuring and predicting species presence: coastal sage scrub case study. In: Hunsaker CT, Goodchild MF, Friedl MA, Case TJ (eds) Spatial uncertainty in ecology. Springer-Verlag, New York, pp 47–71

Clark RW, Brown WS, Stechert R, Zamudio KR (2010) Roads, interrupted dispersal, and genetic diversity in timber rattlesnakes. Conserv Biol 24(4):1059–1069

Clarkin K, Conner A, Furniss MJ, Gibernick B, Love M, Moynan K, Wilson S (2005) National inventory and assessment procedure for identifying barriers to aquatic organism passage at road-stream crossings. US Dep Agric for Serv. http://www.stream.fs.fed.us/publications/PDFs/NIAP.pdf

Colino-Rabanal VJ, Lizana M (2012) Herpetofauna and roads: a review. Basic Appl Herpetol 26:5–31

Colley M, Lougheed SC, Otterbein K, Litzgus JD (2017) Mitigation reduces road mortality of a threatened rattlesnake. Wildlife Res. https://doi.org/10.1071/WR16130

Congress US (1973) Endangered species act. US Code 16:1534–1544

COSEWIC (Committee on the Status of Endangered Wildlife in Canada) (2012) COSEWIC assessment and status report on the Western Toad *Anaxyrus boreas* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xiv + 71 pp. (www.registrelep-sararegistry.gc.ca/default_e.cfm)

COSEWIC (Committee on the Status of Endangered Wildlife in Canada) (2015) COSEWIC assessment and status report on the Northern Red-legged Frog *Rana aurora* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xii + 69 pp. (www.registrelep-sararegistry.gc.ca/default_e.cfm)

Crawford BA (2015) Lessons from terrapin mortality and management on the Jekyll Island Causeway, Georgia, USA. In: Andrews KM, Nanjappa P, Riley SPD (eds) Roads and ecological infrastructure. Concepts and applications for small animals. Johns Hopkins University Press, Baltimore, pp 21–41

D'Amico M, Román J, De los Reyes L, Revilla E (2015) Vertebrate road-kill patterns in Mediterranean habitats: who, when and where. Biol Conserv 191:234–242

D'Amico M, Périquet S, Román J, Revilla E (2016) Road avoidance responses determine the impact of heterogeneous road networks at a regional scale. J Appl Ecol 53(1):181–190

Dodd CK, Barichivich WJ, Smith LL (2004) Effectiveness of a barrier wall and culverts in reducing wildlife mortality on a heavily traveled highway in Florida. Biol Conserv 118(5):619–631

Eigenbrod F, Hecnar SJ, Fahrig L (2008) The relative effects of road traffic and forest cover on anuran populations. Biol Conserv 141(1):35–46

Evelyn CJ, Sweet SS (2012) Conservation status of amphibians and reptiles on USDA National Forests, Pacific Southwest Region, 2012. Prepared for: USDA National Forest Service, Region 5, Pacific Southwest Region

Fahrig L, Rytwinski T (2009) Effects of roads on animal abundance: an empirical review and synthesis. Ecol Soc 14. http://www.ecologyandsociety.org/vol14/iss11/art21

Fahrig L, Pedlar JH, Pope SE, Taylor PD, Wegner JF (1995) Effect of road traffic on amphibian density. Biol Conserv 73(3):177–182

Fellers GM, Kleeman PM (2007) California red-legged frog (*Rana draytonii*) movement and habitat use: implications for conservation. J Herpetol 41(2):276–286

Forman RT, Sperling D, Bissonette JA, Clevenger AP, Cutshall CD, Dale VH, Fahrig L, France R, Goldman CR, Heanue K, Jones JA (2003) Road ecology. Science and Solutions. Island Press, Washington

Furniss MJ, Roelofs TD, Yee CS (1991) Road construction and maintenance. Am Fish Soc Special Publ 19:297–323

Gibbs JP (1998) Amphibian movements in response to forest edges, roads, and streambeds in southern New England. J Wildl Manage 62:584–589

Gibbs JP, Shriver WG (2002) Estimating the effects of road mortality on turtle populations. Conserv Biol 16(6):1647–1652

Gibbs JP, Shriver WG (2005) Can road mortality limit populations of pool-breeding amphibians? Wetl Ecol Manag 13:281–289

Glista DJ, DeVault TL, DeWoody JA (2008) Vertebrate road mortality predominantly impacts amphibians. Herpetol Conserv Biol 3(1):77–87

Goodman RH, Stewart GR (2000) Aquatic home ranges of female Western Pond Turtles, *Clemmys marmorata*, at two sites in Southern California. Chelonian Conserv Biol 3(4):743–744

Gregory PT (1984) Communal denning in snakes. In: Seigel RA, Hunt LE, Knight JL, Maralet LA, Zuschlag NL (eds) Contributions to vertebrate ecology and systematics: a tribute to Henry S. Fitch. University of Kansas Museum of Natural History Special Publication 10:57–75

Halstead BJ, Skalos SM, Wylie GD, Casazza ML (2015) Terrestrial ecology of semi-aquatic giant gartersnakes (*Thamnophis gigas*). Herpetol Conserv Bio 10(2):633–644

Hayes MP, Rombough CJ, Hayes CB (2007) Natural History: *Rana aurora* (Northern red-legged frog) movement. Herpetol Rev 38:192–193

Hensley FR, Jones TR, Maxwell MS, Adams LJ, Nedella NS (2010) Demography, terrestrial behavior, and growth of Sonora mud turtles (*Kinosternon sonoriense*) in an extreme habitat. Herpetol Monogr 24:174–193

Hermann HW, Pozarowski KM, Ochoa A, Schuett GW (2017) An interstate highway affects gene flow in a top reptilian predator (*Crotalus atrox*) of the Sonoran Desert. Conserv Genet 18:911–924

Hickman JC (ed) (1993) The Jepson manual of higher plants of California. University of California Press, Berkeley

Hobday AJ, Smith ADM, Stobutzki IC, Bulman C, Daley R, Dambacher JM, Deng RA, Dowdney J, Fuller M, Furlani D, Griffiths SP (2011) Ecological risk assessment for the effects of fishing. Fish Res 108(2):372–384

Houlahan JE, Findlay CS (2003) The effects of adjacent land use on wetland amphibian species richness and community composition. Can J Fish Aquat Sci 60:1078–1094

Hozo SP, Djulbegovic B, Hozo I (2005) Estimating the mean and variance from the median, range, and the size of a sample. BMC Med Res Methodol 5(1):1

IUCN (2017) The IUCN Red List of Threatened Species. Version 2017-1. http://www.iucnredlist.org

Jackson ND, Fahrig L (2011) Relative effects of road mortality and decreased connectivity on population genetic diversity. Biol Conserv 144(12):3143–3148

Jackson SD, Langen TA, Marsh DM, Andrews KM (2015) Natural history and physiological characteristics of small animals in relation to roads. In: Andrews KM, Nanjappa P, Riley SPD (eds) Roads and ecological infrastructure. Concepts and applications for small animals. Johns Hopkins University Press, Baltimore, pp 21–41

Jacobson SL, Bliss-Ketchum LL, Rivera CE, Smith WP (2016) A behavior-based framework for assessing barrier effects to wildlife from vehicle traffic volume. Ecosphere 7(4):e01345

Jaeger JA (2000) Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Land Ecol 15(2):115–130

Jaeger JA, Bowman J, Brennan J, Fahrig L, Bert D, Bouchard J, Charbonneau N, Frank K, Gruber B, von Toschanowitz KT (2005) Predicting when animal populations are at risk from roads: an interactive model of road avoidance behavior. Ecol Model 185(2):329–348

Januchowski-Hartley SR, McIntyre PB, Diebel M, Doran PJ, Infante DM, Joseph C, Allan JD (2013) Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. Front Ecol Environ 11(4):211–217

Jochimsen DM, Peterson CR, Andrews KM, Gibbons JW, Drawer E (2004) A literature review of the effects of roads on amphibians and reptiles and the measures used to minimize those effects. USDA Forest Service, Idaho Fish and Game Department, Washington, DC

Jochimsen DM, Peterson CR, Harmon LJ (2014) Influence of ecology and landscape on snake road mortality in a sagebrush-steppe ecosystem. Anim Conserv 17(6):583–592

Jones TR, Babb RD, Hensley FR, LiWanPo C, Sullivan BK (2011) Sonoran Desert snake communities at two sites: concordance and effects of increased road traffic. Herpetol Conserv Biol 6(1):61–71

Kemp PS, O'hanley JR (2010) Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. Fish Manag Ecol 17(4):297–322

Klauber LM (1931) A statistical survey of the snakes of the southern border of California. Bull Zool Soc San Diego 8:1–93

Kwiatkowski MA, Schuett GW, Repp RA, Nowak EM, Sullivan BK (2008) Does urbanization influence the spatial ecology of Gila monsters in the Sonoran Desert? J Zool 276(4):350–357

Langen TA, Ogden KM, Schwarting LL (2009) Predicting hot spots of herpetofauna road mortality along highway networks. J Wildl Manag 73(1):104–114

Langen TA, Andrews KM, Brady SP, Karraker NE, Smith DJ (2015a) Road effects on habitat quality for small animals. In: Andrews KM, Nanjappa P, Riley SPD (eds) Roads and ecological infrastructure. Concepts and applications for small animals. Johns Hopkins University Press, Baltimore, pp 21–41

Langen TA, Gunson KE, Jackson SD, Smith DJ, Ruediger W (2015b) Planning and designing mitigation of road effects on small animals. In: Andrews KM, Nanjappa P, Riley SPD (eds) Roads and ecological infrastructure. Concepts and applications for small animals. Johns Hopkins University Press, Baltimore, pp 146–177

Langton TES (2015) A history of small animal road ecology. Roads and ecological infrastructure. Concepts and applications for small animals. Johns Hopkins University Press, Baltimore, pp 21–41

Lannoo MJ (2005) Amphibian declines: the conservation status of United States species. University of California Press, Berkeley

Levine KK (2013) California amphibian and reptile crossing preliminary investigation. Report to Caltrans Division of Environmental Planning

Linkov I, Satterstrom FK, Kiker G, Batchelor C, Bridges T, Ferguson E (2006) From comparative risk assessment to multi-criteria decision analysis and adaptive management: recent developments and applications. Environ Int 32(8):1072–1093

Litvaitis JA, Tash JP (2008) An approach toward understanding wildlife-vehicle collisions. Environ Manag 42(4):688–697

Loraamm RW, Downs JA (2016) A wildlife movement approach to optimally locate wildlife crossing structures. Int J Geogr Inf Sci 30(1):74–88

Mace GM, Collar NJ, Gaston KJ, Hilton-Taylor C, Akçakaya HR, Leader-Williams N, Milner-Gulland EJ, Stuart SN (2008) Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv Biol 22(6):1424–1442

Marsh DM, Jaeger JAG (2015) Direct effects of roads on small animal populations. Roads and ecological infrastructure. Concepts and applications for small animals. Johns Hopkins University Press, Baltimore, pp 21–41

Martinez-Solano I, Jockusch EL, Wake DB (2007) Extreme population subdivision throughout a continuous range: phylogeography of *Batrachoseps attenuatus* (Caudata: Plethodontidae) in western North America. Mol Ecol 16(20):4335–4355

Mazerolle MJ, Huot M, Gravel M (2005) Behavior of amphibians on the road in response to car traffic. Herpetologica 61(4):380–388

Mccardle LD, Fontenot CL (2016) The influence of thermal biology on road mortality risk in snakes. J Thermal Biol 56:39–49

Mitrovich MJ (2006) A case study in conservation science: The spatial ecology and evolutionary history of the coachwhip snake (*Masticophis flagellum*) and striped racer (*M. lateralis*). Ph.D. dissertation. University of California, Davis, and San Diego State University. San Diego

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403(6772):853–858

NatureServe (2017) NatureServe explorer: An online encyclopedia of life [web application]. Version 7.1. NatureServe, Arlington, Virginia. http://explorer.natureserve.org. (Accessed: May 25, 2017)

Orłowski G (2007) Spatial distribution and seasonal pattern in road mortality of the common toad *Bufo bufo* in an agricultural landscape of south-western Poland. Amphibia-Reptilia 28(1):25–31

Peaden JM, Tuberville TD, Buhlmann KA, Nafus MG, Todd BD (2016) Delimiting road-effect zones for threatened species: implications for mitigation fencing. Wildl Res 42(8):650–659

Peaden JM, Nowakowski AJ, Tuberville TD, Buhlmann KA, Todd BD (2017) Effects of roads and roadside fencing on movements, space use, and carapace temperatures of a threatened tortoise. Biol Conserv 214:13–22

Pianka ER (1966) Convexity, desert lizards, and spatial heterogeneity. Ecology 47(6):1055–1059

Pilliod DS, Welty JL, Stafford R (2013) Terrestrial movement patterns of western pond turtles (*Actinemys marmorata*) in central California. Herpetol Conserv Bio 8(1):207–221

Polak T, Rhodes JR, Jones D, Possingham HP (2014) Optimal planning for mitigating the impacts of roads on wildlife. J Appl Ecol 51(3):726–734

Rathbun GB, Scott NJ Jr, Murphey TG (2002) Terrestrial habitat use by Pacific pond turtles in a Mediterranean climate. Southwest Nat 47(2):225–235

Reese DA, Welsh HH (1997) Use of terrestrial habitat by western pond turtles, *Clemmys marmorata*: implications for management. In Proceedings: Conservation, restoration, and management of tortoises and turtles–an international conference. State University of New York, Purchase, New York, pp 352–357)

Reid BN, Peery MZ (2014) Land use patterns skew sex ratios, decrease genetic diversity and trump the effects of recent climate change in an endangered turtle. Divers Distrib 20(12):1425–1437

Roe JH, Gibson J, Kingsbury BA (2006) Beyond the wetland border: estimating the impact of roads for two species of water snakes. Biol Conserv 130(2):161–168

Rosen PC, Lowe CH (1994) Highway mortality of snakes in the Sonoran Desert of southern Arizona. Biol Conserv 68(2):143–148

Rosenberg D, Gervais J, Vesely D, Barnes S, Holts L, Horn R, Swift R, Todd L, Yee C (2009) Conservation assessment of the Western pond turtle in Oregon (*Actinemys marmorata*). USDI Bureau of Land Management and Fish and Wildlife Service, USDA Forest Service Region 6, Oregon

Rouse JD, Willson RJ, Black R, Brooks RJ (2011) Movement and spatial dispersion of *Sistrurus catenatus* and *Heterodon platirhinos*: implications for interactions with roads. Copeia 3:443–456

Row JR, Blouin-Demers G, Weatherhead PJ (2007) Demographic effects of road mortality in black ratsnakes (*Elaphe obsoleta*). Biol Conserv 137(1):117–124

Rudolph DC, Burgdorf SJ, Conner RN, Schaefer RR (1999) Preliminary evaluation of the impact of roads and associated vehicular traffic on snake populations in eastern Texas. In: Proceedings of the Third International Conference on Wildlife Ecology and Transportation. FL-ER-73-99. Evink GL, Garrett P, Zeigler D (eds) Florida Department of Transportation, Tallahassee, Florida, pp 129–136

Rytwinski T, Fahrig L (2012) Do species life history traits explain population responses to roads? A meta-analysis. Biol Conserv 147(1):87–98

Rytwinski T, Fahrig L (2013) Why are some animal populations unaffected or positively affected by roads? Oecologia 173(3):1143–1156

Rytwinski T, Fahrig L (2015) The impacts of roads and traffic on terrestrial animal populations. Handbook of Road Ecology. Wiley, New York, pp 237–246

Semlitsch RD (1998) Biological delineation of terrestrial buffer zones for pond-breeding salamanders. Conserv Biol 12(5):1113–1119

Semlitsch RD (2008) Differentiating migration and dispersal processes for pond-breeding amphibians. J Wildl Manag 72(1):260–267

Semlitsch RD, Bodie JR (2003) Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles. Conserv Biol 17(5):1219–1228

Shilling F, Waetjen D (2017) California Roadkill Observation System. UC Davis Road Ecology Center. http://wildlifecrossing.net/california(accessed April 2017)

Siers SR, Reed RN, Savidge JA (2016) To cross or not to cross: modeling wildlife road crossings as a binary response variable with contextual predictors. Ecosphere 7(5):19

Stebbins RC, McGinnis SM (2012) Field guide to amphibians and reptiles of California, vol 103. University of California Press, Berkeley

Steen DA, Aresco MJ, Beilke SG, Compton BW, Condon EP, Dodd KC, Forrester H, Gibbons JW, Greene JL, Johnson G, Langen TA (2006) Relative vulnerability of female turtles to road mortality. Anim Conserv 9(3):269–273

Sullivan BK (2012) Road riding. In: McDiarmid RW (ed) Reptile biodiversity: standard methods for inventory and monitoring. University of California Press, Oakland, CA, pp 215–218

Suter GW II (2016) Ecological risk assessment. CRC Press, Boca Raton, FL

Thomson RC, Wright AN, Shaffer HB (2016) California amphibian and reptile species of special concern. University of California Press, Oakland, CA

Trenham PC (1998) Demography, migration, and metapopulation structure of pond-breeding salamanders. Ph.D. dissertation. University of California, Davis

Trenham PC, Koenig WD, Shaffer HB (2001) Spatially autocorrelated demography and interpond dispersal in the salamander *Ambystoma californiense*. Ecology 82(12):3519–3530

Trenham PC, Koenig WD, Mossman MJ, Stark SL, Jagger LA (2003) Regional dynamics of wetland-breeding frogs and toads: turnover and synchrony. Ecol Appl 13(6):1522–1532

US Fish and Wildlife (USFWS) (2016) United States species: Endangered and threatened wildlife (50 CFR 17.11). https://www.fws.gov/endangered/species/us-species.html (accessed August 2016)

US Fish and Wildlife Service (USFWS) (2002) Recovery plan for the California red-legged frog (*Rana aurora draytonii*). US Fish and Wildlife Service, Portland, Oregon, viii + 173 pp

US Fish and Wildlife Service (USFWS) (2009) *Rana pretiosa.* Species assessment and listing priority assignment form. USFWS Region 1, Portland

US Fish and Wildlife Service (USFWS) (2011) Alameda whipsnake (*Masticophis lateralis euryxanthus*) 5-year review summary and evaluation. US Fish and Wildlife Service, Sacramento, CA

van der Ree R, Smith DJ, Grilo C (2015) Handbook of road ecology. Wiley, New York

Vangel MG (2015) Tolerance interval. Statistics Reference Online. Wiley StatsRef, New York, pp 1–7

Vences M, Wake DB (2007) Speciation, species boundaries and phylogeography of amphibians. Amphib Biol 7:2613–2671

Watson JW, McAllister KR, Pierce DJ (2003) Home ranges, movements, and habitat selection of Oregon Spotted Frogs (*Rana pretiosa*). J Herp 37(2):292–300

Young KV, Young AT (2000) Final report: scientific study of the flat-tailed horned lizard, *Phrynosoma mcallii*. US Dept. of Navy Contracts N68711-95-LT-C0032, N68711-95-LT-C0035. 72 pp

Zimmermann Teixeira F, Kindel A, Hartz S, Mitchell S, Fahrig L (2017) When road-kill hotspots do not indicate the best sites for road-kill mitigation. J Appl Ecol 54(5):1544–1551

Chapter 3. Spatial Mapping - California Essential Habitat Connectivity Lands, Highways, and High-Risk Species

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Introduction

The California Department of Transportation (Caltrans) and California Department of Fish and Wildlife (CDFW) commissioned the California Essential Habitat Connectivity (CEHC) Project because a functional network of connected wildlands is essential to the continued support of California's diverse natural communities in the face of human development and climate change. This report is also intended to make transportation and land-use planning more efficient and less costly, while helping reduce dangerous wildlife-vehicle collisions (Spencer et al. 2010).

The statewide essential connectivity network consists of 850 relatively intact and well conserved Natural Landscape Blocks (ranging from 2,000 to about 3.7 million acres each) with over 1,000 potential connections among them. The 192 Essential Connectivity Areas represent principle connections between the Natural Landscape Blocks within which land conservation and management actions should be prioritized to maintain and enhance ecological connectivity (Spencer et al. 2010).

CEHC maps and spatial layers depict large, relatively natural habitat blocks that support native biodiversity and areas considered essential for regional large-scale connectivity. To better represent natural areas not included in the large-scale CEHC map but large enough to support sensitive amphibian and reptile populations in California, we also incorporated smaller natural areas between 25 to 2000 acres (10 to 809 ha) that were included in the CEHC map database for regional and local scale analyses. We then combined these into a spatial geodatabase to crosswalk the CEHC Map, State Highways, and the California amphibian and reptile road risk assessment (Brehme et al. 2018).

The spatial geodatabase includes:

1. CEHC natural habitat blocks greater than 10 ha (25 ac).
2. Range maps of high and very-high risk amphibian and reptile species.
3. California highway segments that intersect the ranges of high and very high-risk amphibian and reptile species.
4. California highway segments that intersect the ranges of high and very high-risk amphibian and reptile species and CEHC lands.
5. Postmile markers of all California highway segments that intersect the ranges of high and very high-risk amphibian and reptile species and CEHC lands.
6. The total number of high and very-high risk species ranges that intersect the highway segments and CEHC lands.

This geodatabase was designed to be a useful planning tool for Caltrans to quickly identify road segments that may warrant planning for increased connectivity of high-risk amphibian and reptile species.

Methods

The GIS analyses were conducted using ArcGIS 10.5.1 software. Species range and highway layers were obtained from Caltrans and CDFW.

Species Range Layers

Species ranges were obtained from the ARSSC_DFG_HerpRoadRiskRanges shapefile provided by Dr. Amber Wright (University of Hawaii), co-author of the California amphibian and reptile species of special concern (Thomson et al. 2016), and the California Wildlife Habitat Relationships (CWHR) GIS database (downloaded from the CDFW, *https://wildlife.ca.gov/Conservation/Planning/Data-and-Tools* on June 16, 2016). Updated range layers for 4 species were provided by email from CDFW in April 2020. All species range layers were merged into a single feature class, ARSSC_DFG_CWHR_SppRoadRiskRanges (CWHR). Table 1 lists the species that were included and the source of the GIS layers.

Table 1. List of High and Very-High Risk Species and GIS Source.

Scientific Name	Common Name	Cons. Status[a]	Species Group	GIS Source
Actinemys marmorata	Northern Western Pond Turtle	ARSSC 3	Turtle	ARSSC (2016)
Actinemys pallida	Southern Western Pond Turtle	ARSSC 1	Turtle	CWHR (2020)
Ambystoma californiense[1]	California Tiger Salamander	THR[F,S], END[F]	Salamander	ARSSC (2016)
Ambystoma macrodactylum croceum	Santa Cruz Long-toed Salamander	END[F,S]	Salamander	ARSSC (2016)
Ambystoma macrodactylum sigillatum	Southern Long-toed Salamander	ARSSC 2	Salamander	CWHR (2020)
Anaxyrus californicus	Arroyo Toad	END[F],ARSSC 1	Toad	ARSSC (2016)
Anaxyrus canorus	Yosemite Toad	THR[F],ARSSC 1	Toad	ARSSC (2016)
Anaxyrus cognatus	Great Plains Toad		Toad	ARSSC (2016)
Anaxyrus exsul	Black Toad	THR[S]	Toad	ARSSC (2016)
Anaxyrus woodhousii	Woodhouse's Toad		Toad	CWHR (2016)
Arizona elegans occidentalis	California Glossy Snake	ARSSC 1	Snake-Terrestrial	ARSSC (2016)
Aspidoscelis tigris stejnegeri[2]	San Diegan Tiger Whiptail	ARSSC 2	Lizard	CWHR (2016)
Coleonyx switaki	Switak's Banded Gecko	THR[S]	Lizard	CWHR (2016)
Coluber constrictor	North American racer		Snake-Terrestrial	ARSSC (2016)
Crotalus atrox	Western Diamond-backed Rattlesnake		Snake-Terrestrial	ARSSC (2016)
Crotalus cerastes	Sidewinder		Snake-Terrestrial	CWHR (2016)
Crotalus mitchellii	Speckled Rattlesnake		Snake-Terrestrial	ARSSC (2016)
Crotalus oreganus	Western Rattlesnake		Snake-Terrestrial	ARSSC (2016)
Crotalus ruber	Red Diamond Rattlesnake	ARSSC 3	Snake-Terrestrial	ARSSC (2016)
Crotalus scutulatus	Mojave Rattlesnake		Snake-Terrestrial	CWHR (2016)
Crotalus stephensi	Panamint Rattlesnake		Snake-Terrestrial	ARSSC (2016)
Diadophis punctatus regalis	Regal ring-necked Snake	ARSSC 2	Snake-Terrestrial	ARSSC (2016)
Dicamptodon ensatus	California Giant Salamander	ARSSC 3	Salamander	ARSSC (2016)
Gambelia copeii	Cope's Leopard Lizard	ARSSC	Lizard	ARSSC (2016)
Gambelia sila	Blunt-nosed Leopard Lizard	END[F]	Lizard	ARSSC (2016)
Gambelia wislizenii	Long-nosed Leopard Lizard		Lizard	CWHR (2016)
Gopherus agassizii	Mohave Desert tortoise	THR[F,S]	Tortoise	ARSSC (2016)

Scientific Name	Common Name	Cons. Status[a]	Species Group	GIS Source
Heloderma suspectum cinctum	Banded Gila Monster	ARSSC	Lizard	ARSSC (2016)
Hypsiglena chlorophaea	Desert Nightsnake		Snake-Terrestrial	CWHR (2016)
Hypsiglena ochrorhyncha	Nightsnake		Snake-Terrestrial	ARSSC (2016)
Incilius alvarius	Sonoran Desert Toad	ARSSC 1	Toad	ARSSC (2016)
Kinosternon sonoriense[3]	Sonora Mud turtle	ARSSC 1	Turtle	ARSSC (2016)
Phyllorhynchus decurtatus	Spotted Leaf-nosed Snake	ARSSC 2	Snake-Terrestrial	CWHR (2016)
Masticophis flagellum	Coachwhip		Snake-Terrestrial	ARSSC (2016)
Masticophis flagellum ruddocki	San Joaquin Coachwhip	ARSSC 2	Snake-Terrestrial	ARSSC (2016)
Masticophis fuliginosus	Baja California Coachwhip	ARSSC 3	Snake-Terrestrial	ARSSC (2016)
Masticophis lateralis	Striped Racer		Snake-Terrestrial	ARSSC (2016)
Masticophis lateralis euryxanthus	Alameda Striped Racer	THR[F,S]	Snake-Terrestrial	CWHR (2020)
Masticophis taeniatus	Striped Whipsnake		Snake-Terrestrial	ARSSC (2016)
Phrynosoma mcallii	Flat-tailed Horned Lizard	THR[F], ARSSC 2	Lizard	ARSSC (2016)
Phrynosoma platyrhinos	Desert Horned Lizard		Lizard	ARSSC (2016)
Rana aurora	Northern Red-legged Frog	ARSSC 2	Frog	ARSSC (2016)
Rana cascadae	Cascades Frog	ARSSC 2	Frog	CWHR (2016)
Rana draytonii	California Red-legged Frog	THR[F], ARSSC 1	Frog	ARSSC (2016)
Rana pretiosa	Oregon Spotted Frog	THR[F], ARSSC 1	Frog	ARSSC (2016)
Salvadora hexalepis	Western Patch-nosed Snake		Snake-Terrestrial	ARSSC (2016)
Salvadora hexalepis virgultea	Coast Patch-nosed Snake	ARSSC 2	Snake-Terrestrial	ARSSC (2016)
Sonora occipitalis	Western Shovel-nosed Snake		Snake-Terrestrial	CWHR (2016)
Sonora semiannulata	Western Groundsnake		Snake-Terrestrial	CWHR (2016)
Spea hammondii	Western Spadefoot	ARSSC 1	Toad	ARSSC (2016)
Taricha granulosa	Rough-skinned Newt		Salamander	ARSSC (2016)
Taricha rivularis	Red-bellied Newt	ARSSC 2	Salamander	ARSSC (2016)
Taricha sierrae	Sierra Newt		Salamander	ARSSC (2016)
Taricha torosa	Coast Range Newt	ARSSC 2	Salamander	ARSSC (2016)
Thamnophis atratus	Aquatic Gartersnake		Snake-Aquatic	ARSSC (2016)
Thamnophis couchii	Sierra Gartersnake		Snake-Aquatic	ARSSC (2016)
Thamnophis elegans	Terrestrial Gartersnake		Snake-Aquatic	ARSSC (2016)
Thamnophis gigas	Giant Gartersnake	THR[F,S]	Snake-Aquatic	ARSSC (2016)
Thamnophis hammondii	Two-striped Gartersnake	ARSSC 2	Snake-Aquatic	ARSSC (2016)
Thamnophis ordinoides	Northwestern Gartersnake		Snake-Aquatic	ARSSC (2016)
Thamnophis sirtalis infernalis[4]	California Red-sided Gartersnake	ARSSC 1	Snake-Aquatic	ARSSC (2016)
Thamnophis sirtalis tetrataenia	San Francisco Gartersnake	END[F,S]	Snake-Aquatic	CWHR (2020)
Trimorphodon lambda	Sonoran Lyresnake		Snake-Terrestrial	ARSSC (2016)
Trimorphodon lyrophanes	California Lyresnake		Snake-Terrestrial	ARSSC (2016)

[a]Conservation Status: THR=Threatened, END= Endangered, Superscripts F and S are used to delineate State and Federal listing status, ARSSC= State Species of Special Concern with Priority Ranking 1-3.

[1]California tiger salamander Sonoma and Santa Barbara distinct population segments are federally endangered while central DPS is federally threatened.

[2]Species range layer for subspecies was not available so the species range for *Aspidoscelis tigris* was used.

[3]Species range does not contain any State highways

[4]Species range layer for subspecies was not available so the species range for *Thamnophis sirtalis spp*., and the South Coast Gartersnake, were used.

Connectivity Areas Layers

Essential Connectivity Areas (ECA), Natural Landscape Blocks (NLB), and Natural Areas_small (NA; Natural areas smaller than 2,000 acres that otherwise meet NLB criteria) from the Essential Connectivity Map geodatabase were provided by CDFW. The ECA and NLB were merged together with NA areas 10 hectares or greater. The resulting layer was then dissolved into a single polygon feature class with a buffer of 100 meters added to it. This connected many of the smaller polygons. This final layer was used to identify CEHC connectivity areas that overlapped with the target species ranges.

Roads Layers

Road features were obtained from the Caltrans 2012 State Highway Network (SHN) geodatabase provided by Caltrans. The roads layer was clipped to the merged Essential Habitat Connectivity layer (Merged NLB_ECA_NA areas) to create a layer of highway segments that occur in essential habitat connectivity areas. This layer was then clipped to select target species ranges (Table 1). The resulting SHN_Lines_SpeciesRanges feature class represents potential highway segments of concern where species ranges at high risk of negative road impacts intersect with both California highways and California Essential Habitat Connectivity lands. Potential highway segments of concern maps for high risk species with conservation status (threatened, endangered, and species of special concern) are presented in Figures 1–35. Potential highway segments of concern maps for high risk species with no conservation status are not presented in this report. Some species range maps are based on greater knowledge and survey efforts than others. Also, most species are patchily distributed across their known ranges. In this feature class, highway segments of concern are based upon the intersection of broad species range maps, CEHC lands, and State highways. Thus, the segments of concern likely over-represent locations of many species in relation to highways. This feature class is meant to represent potential presence of high risk herpetofauna species. Local knowledge or surveys may be needed to verify their presence or absence adjacent to specific highway segments.

Using the SHN_Lines_SpeciesRanges feature class, start and end point vertices were generated for each road segment of concern for each species (PostMileMarkers_SpeciesRanges). The nearest postmile marker along the same route was identified using the Near Analysis. Postmile marker features were identified using a State Highway Postmile shapefile obtained from Caltrans (shn204v3_TenthPM.shp). The distance from the road start/end point to the postmile the Odometer (distance in miles from start of highway to postmile), post mile marker interval, and route identifier of the marker were included in the feature class.

Species Density Layers

A hexagonal grid with an area of 15 km^2 per grid was generated for the entire state of California using the Generate Tessellation tool. This grid was then intersected with the species range layer (ARSSC_DFG_CWHR_SppRoadRiskRanges). The Summary Statistics tool was used to calculate the number of unique species whose ranges fell within each grid cell as well as number of species per group (frogs, toads, lizards, salamanders, terrestrial and aquatic snakes, turtles, and tortoise). This species density grid was intersected with the SHN lines feature class to create a species density overlay of the road network. These features overall and by group are included in a final map package provided to Caltrans. Densities of all high and very-high risk species across the state and associated highway segments are presented in Figures 36 and 37.

Results: Maps High and Very-High Risk Species

Figure 1. Highway Segments of Concern: Northern Western Pond Turtle (*Actinemys marmorata*)

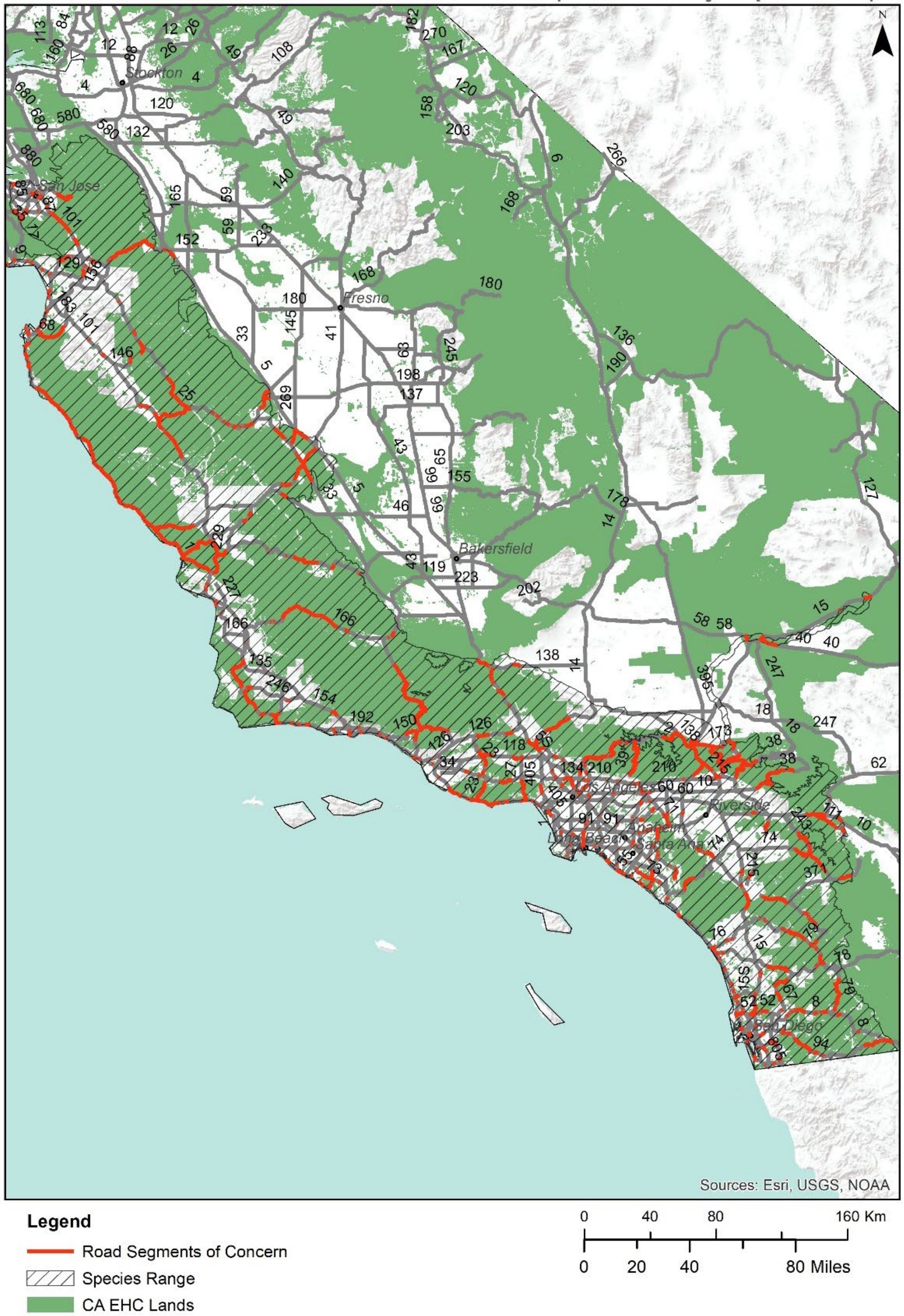

Figure 2. Highway Segments of Concern: Southern Western Pond Turtle (*Actinemys pallida*)

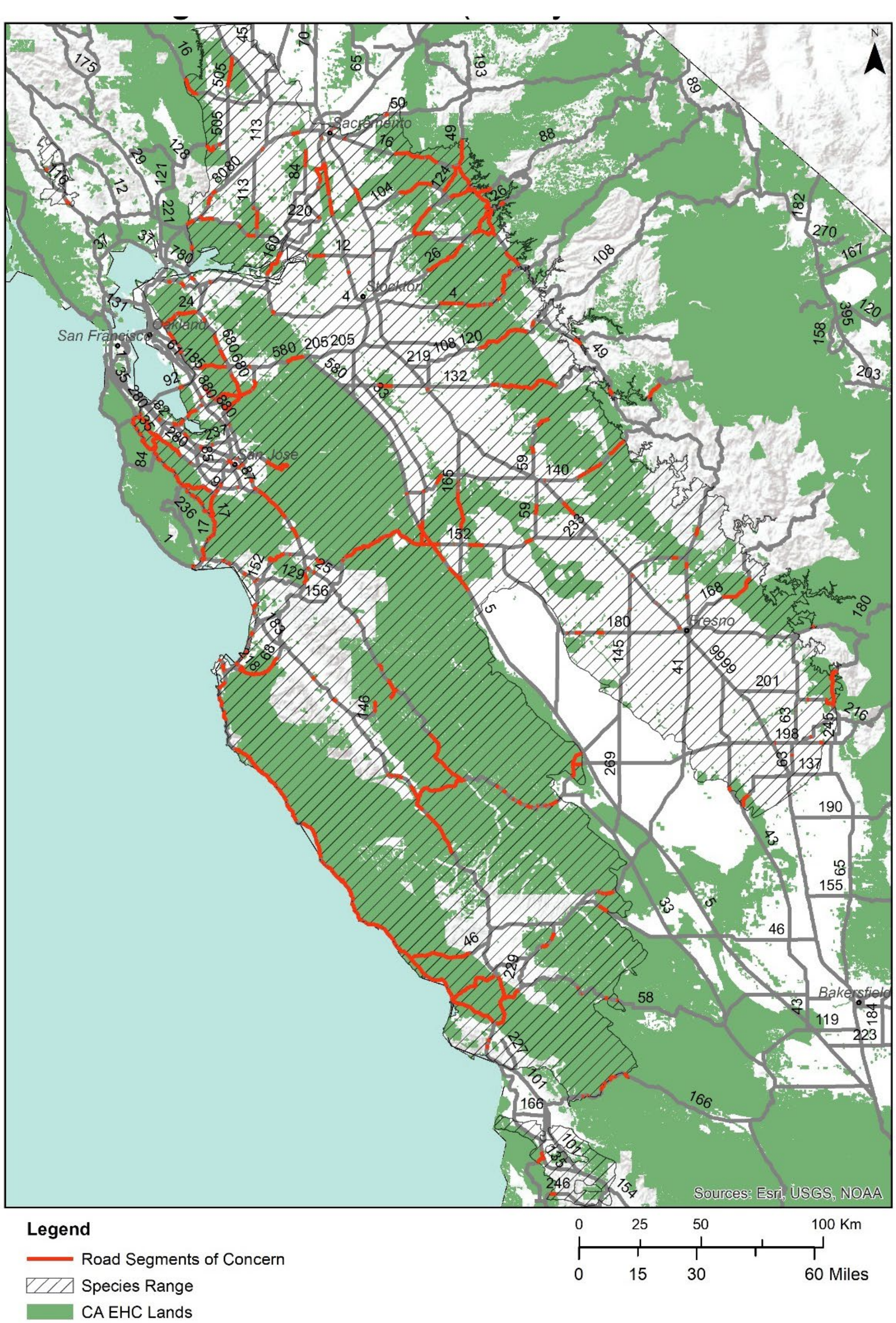

Figure 3. Highway Segments of Concern: California Tiger Salamander (*Ambystoma californiense*)

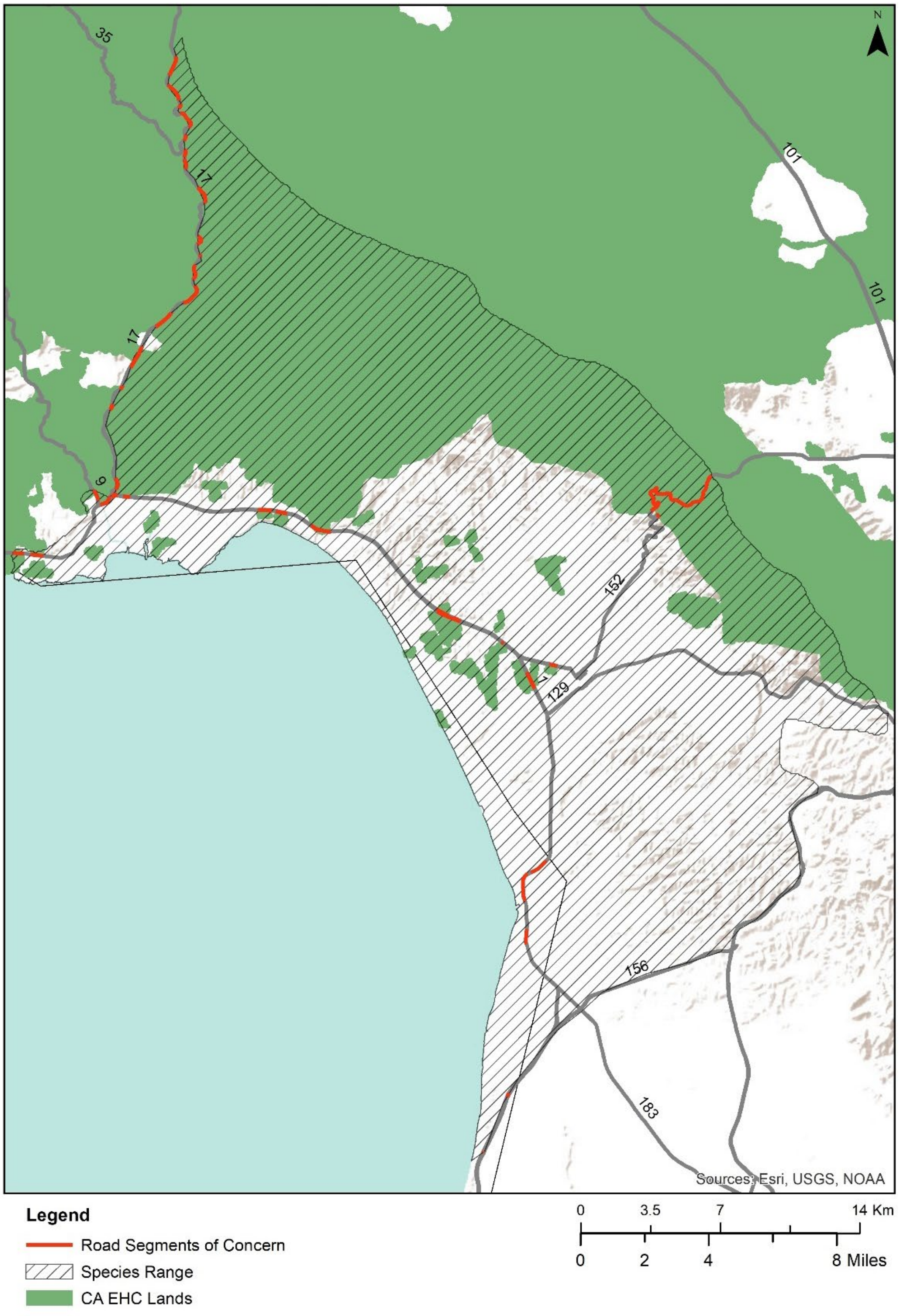

Figure 4. Highway Segments of Concern: Santa Cruz Long-toed Salamander (*Ambystoma macrodactylum croceum*)

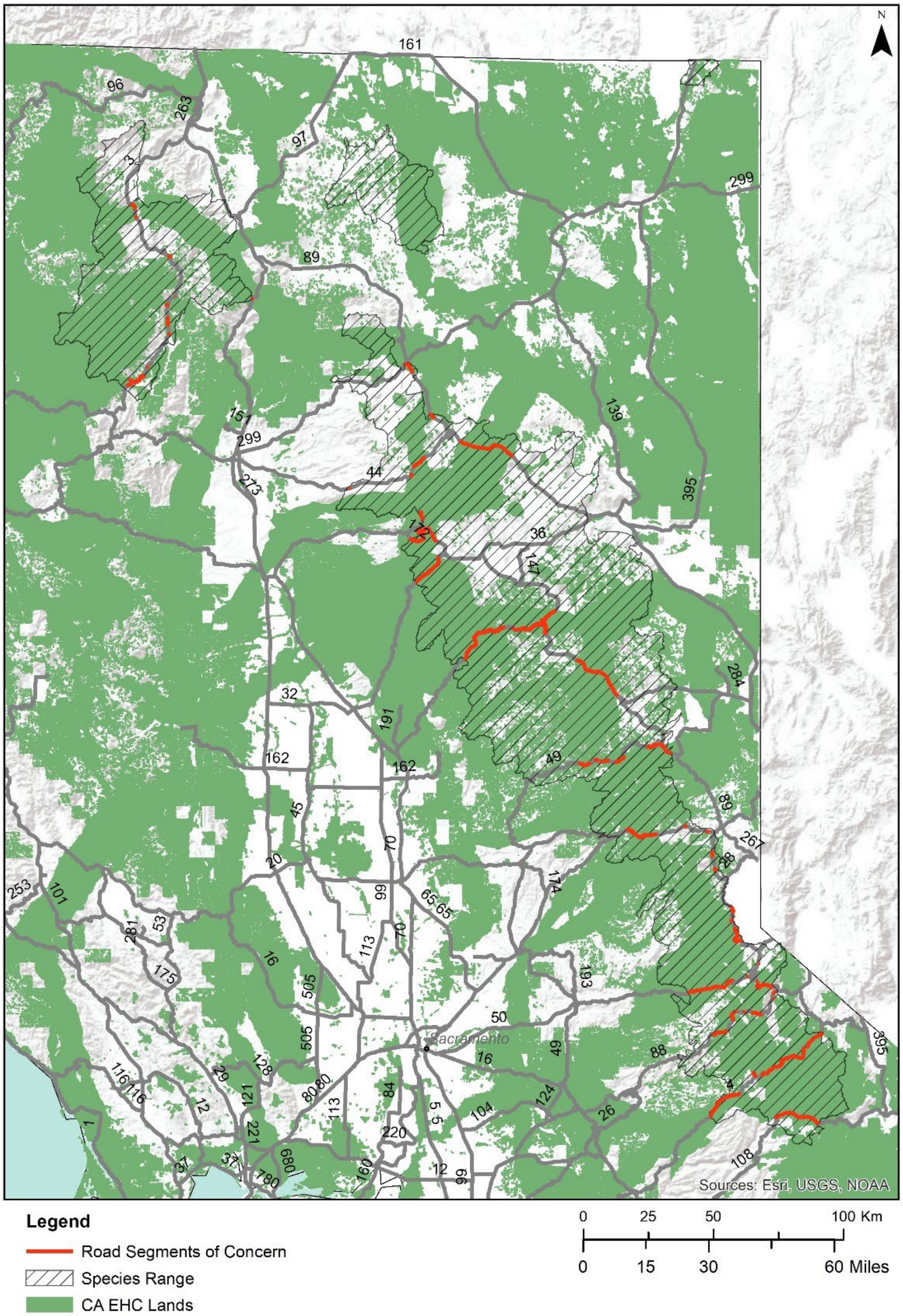

Figure 5. Highway Segments of Concern: Southern Long-toed Salamander (*Ambystoma macrodactylum sigillatum*)

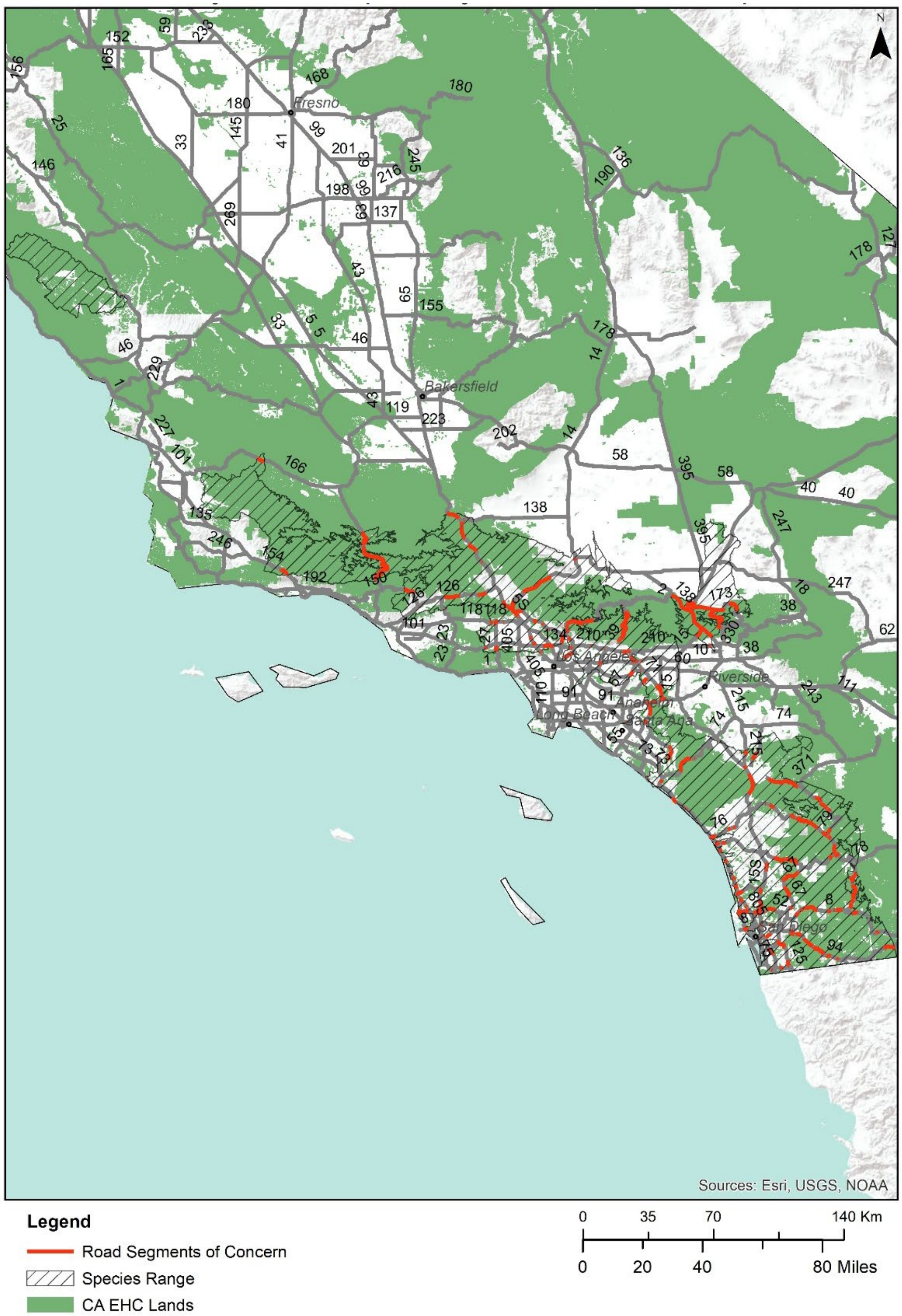

Figure 6. Highway Segments of Concern: Arroyo Toad (*Anaxyrus californicus*)

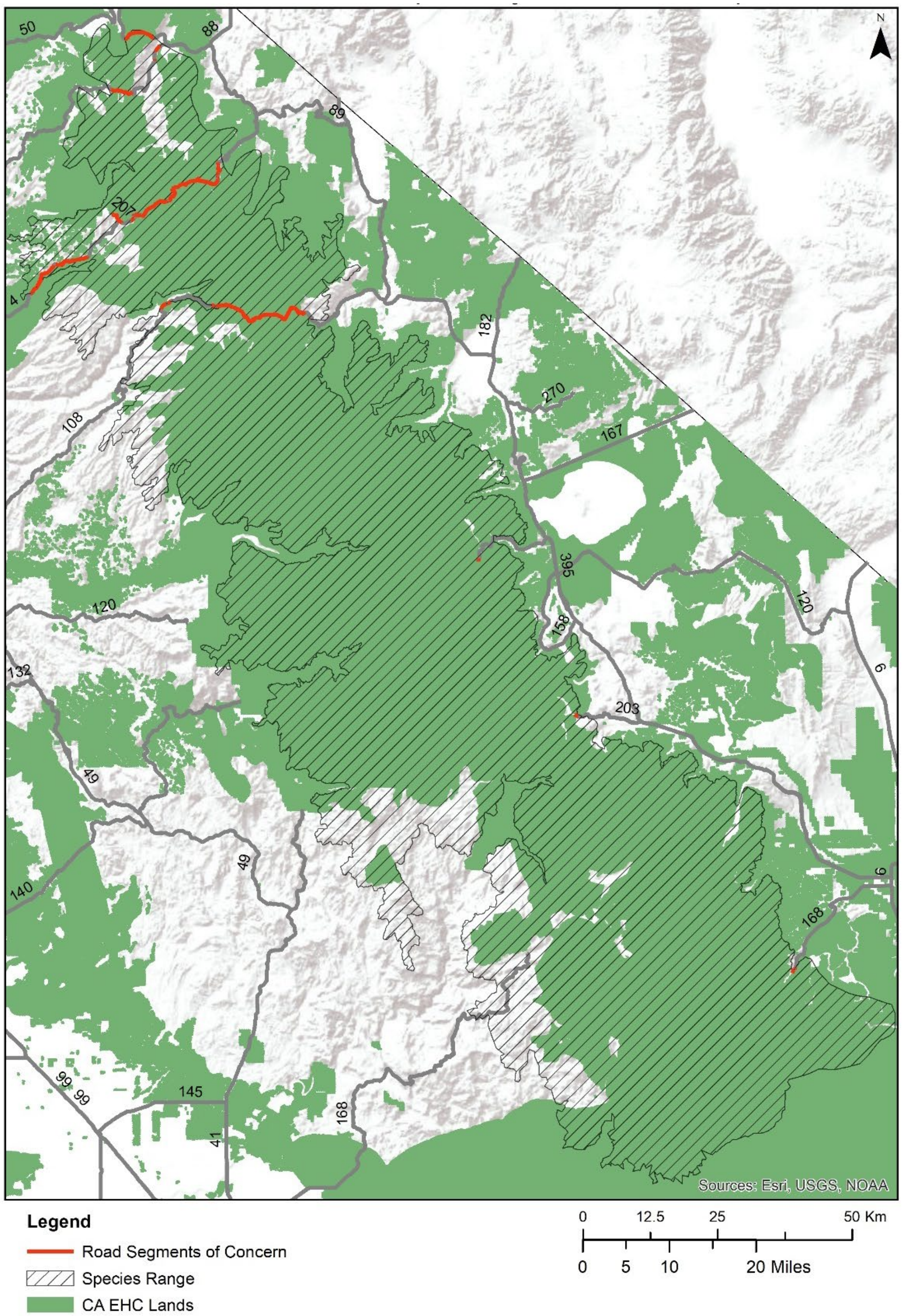

Figure 7. Highway Segments of Concern: Yosemite Toad (*Anaxyrus canorus*)

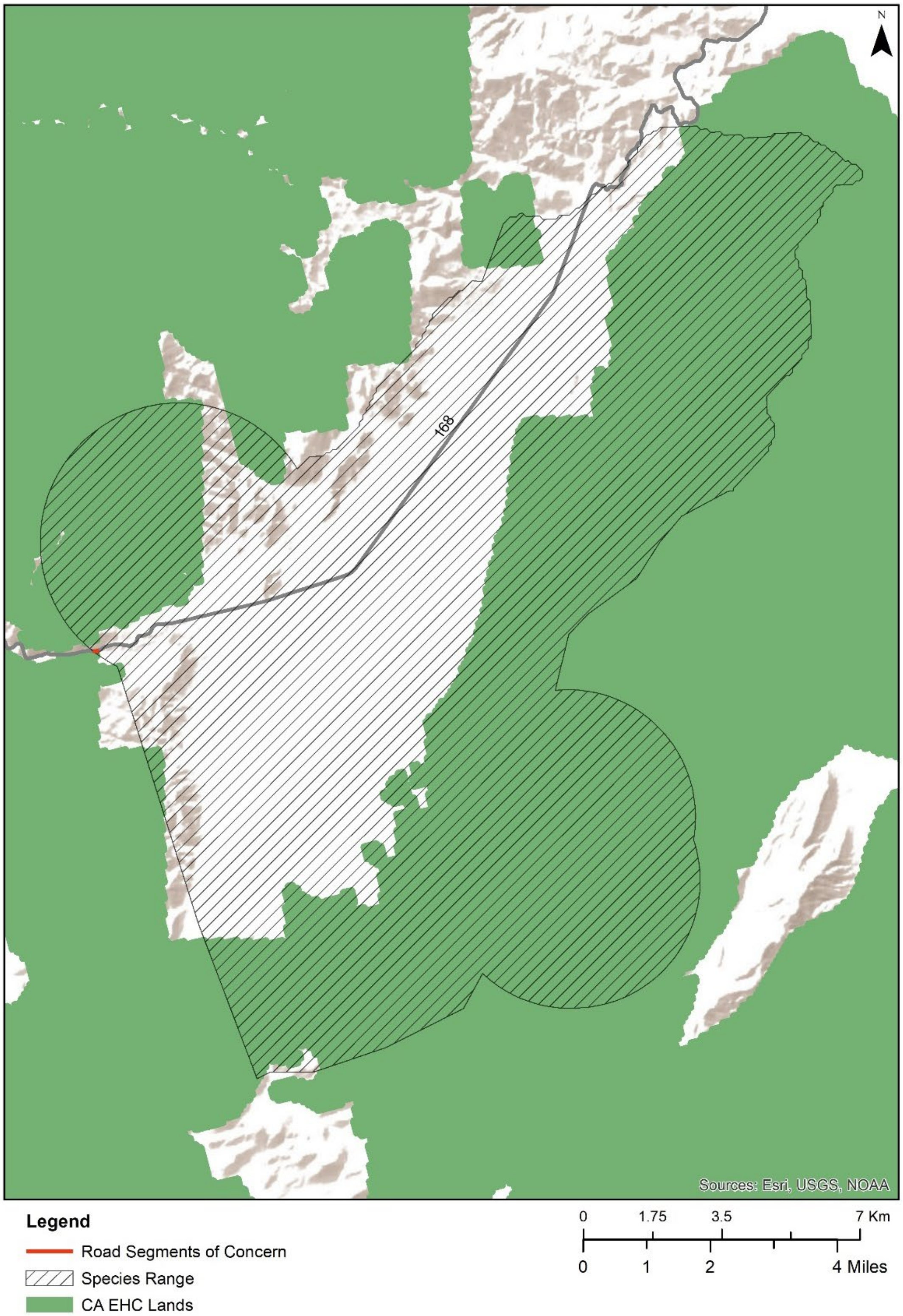

Figure 8. Highway Segments of Concern: Black Toad (*Anaxyrus exsul*)

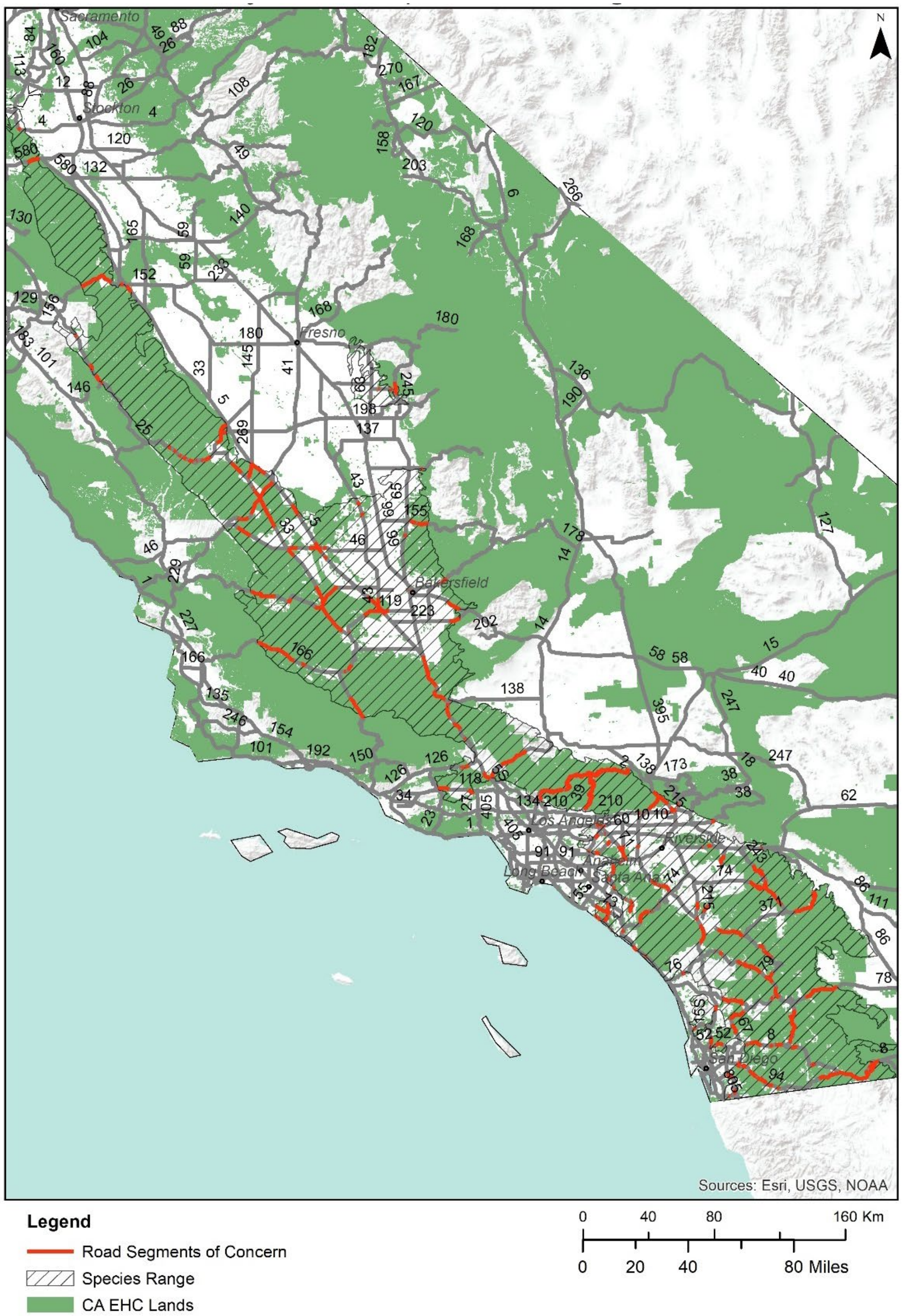

Figure 9. Highway Segments of Concern: California Glossy Snake (*Arizona elegans occidentalis*)

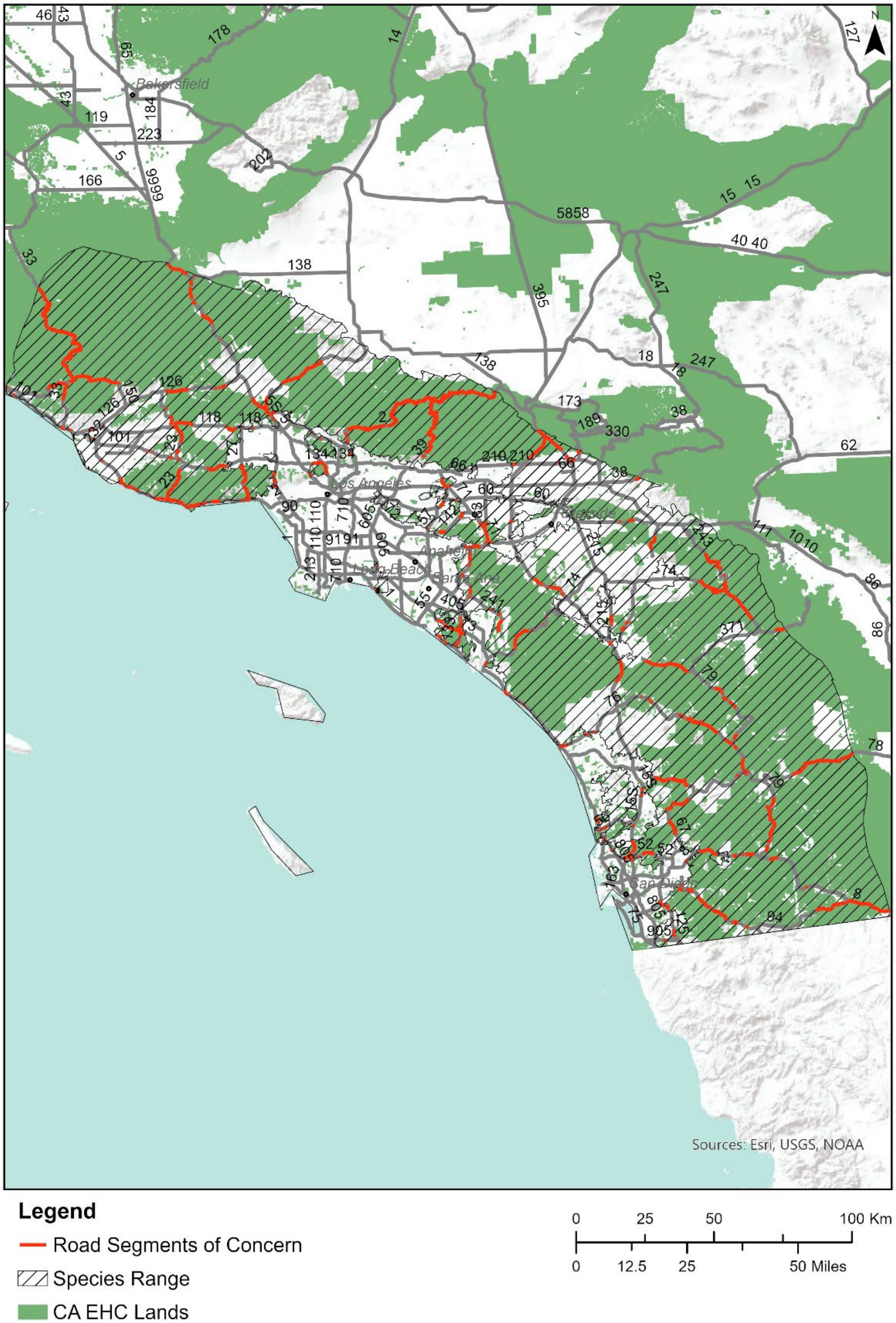

Figure 10. Highway Segments of Concern: San Diegan Tiger Whiptail (*Aspidoscelis tigris stejnegeri*)

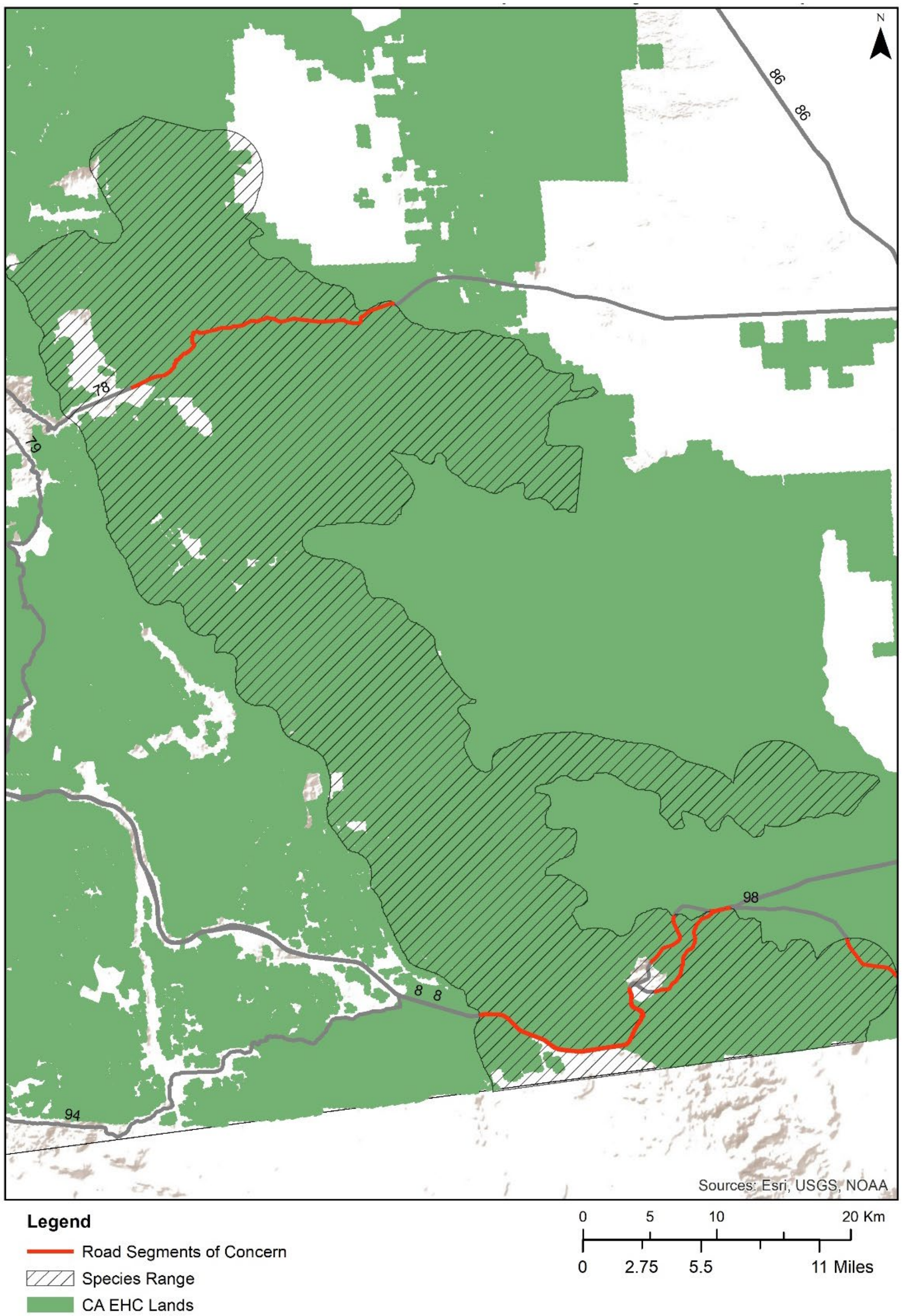

Figure 11. Highway Segments of Concern: Switak's Banded Gecko (*Coleonyx switaki*)

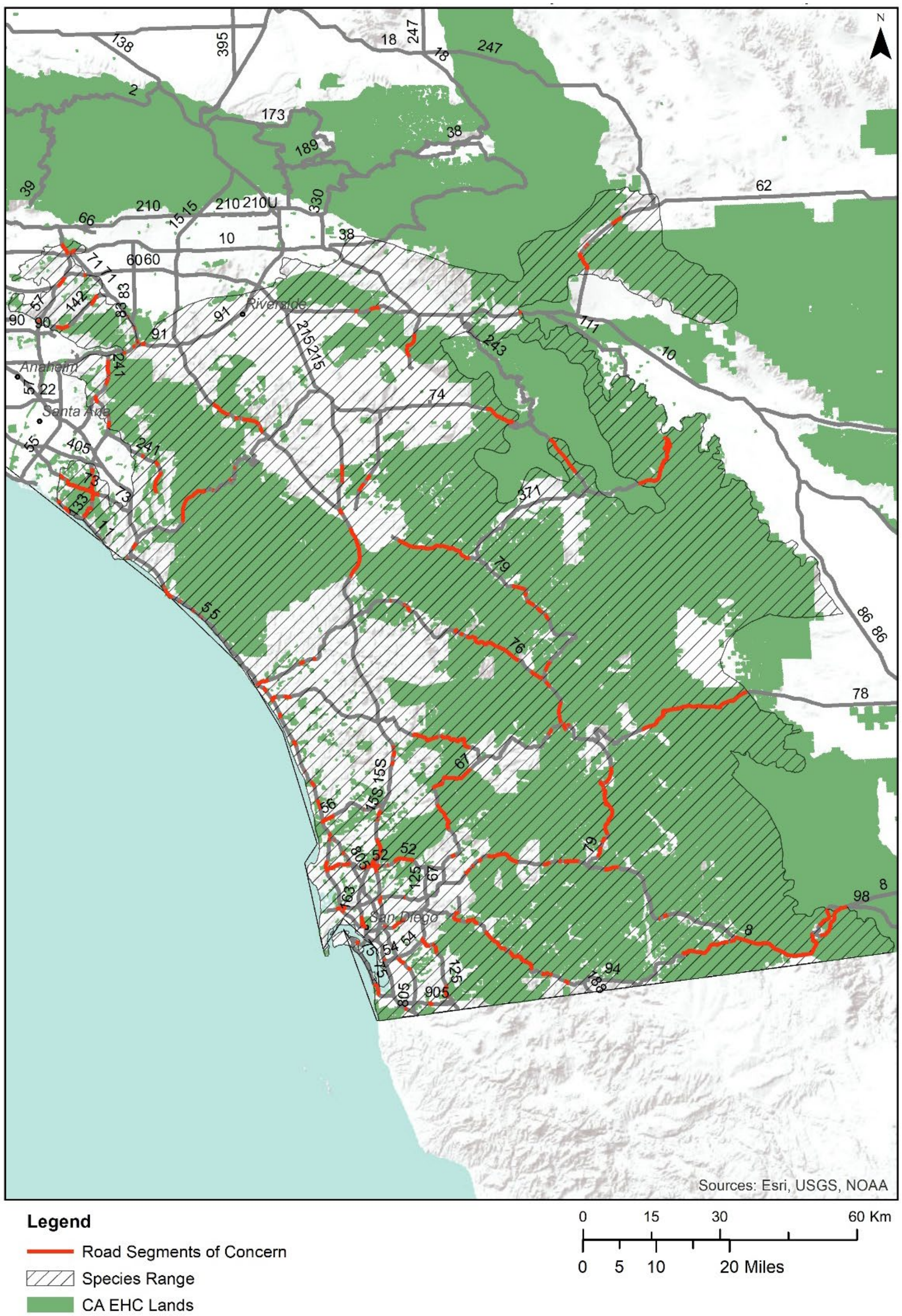

Figure 12. Highway Segments of Concern: Red Diamond Rattlesnake (*Crotalus ruber*)

Figure 13. Highway Segments of Concern: Regal Ring-necked Snake (*Diadophis punctatus regalis*)

Figure 14. Highway Segments of Concern: California Giant Salamander (*Dicamptodon ensatus*)

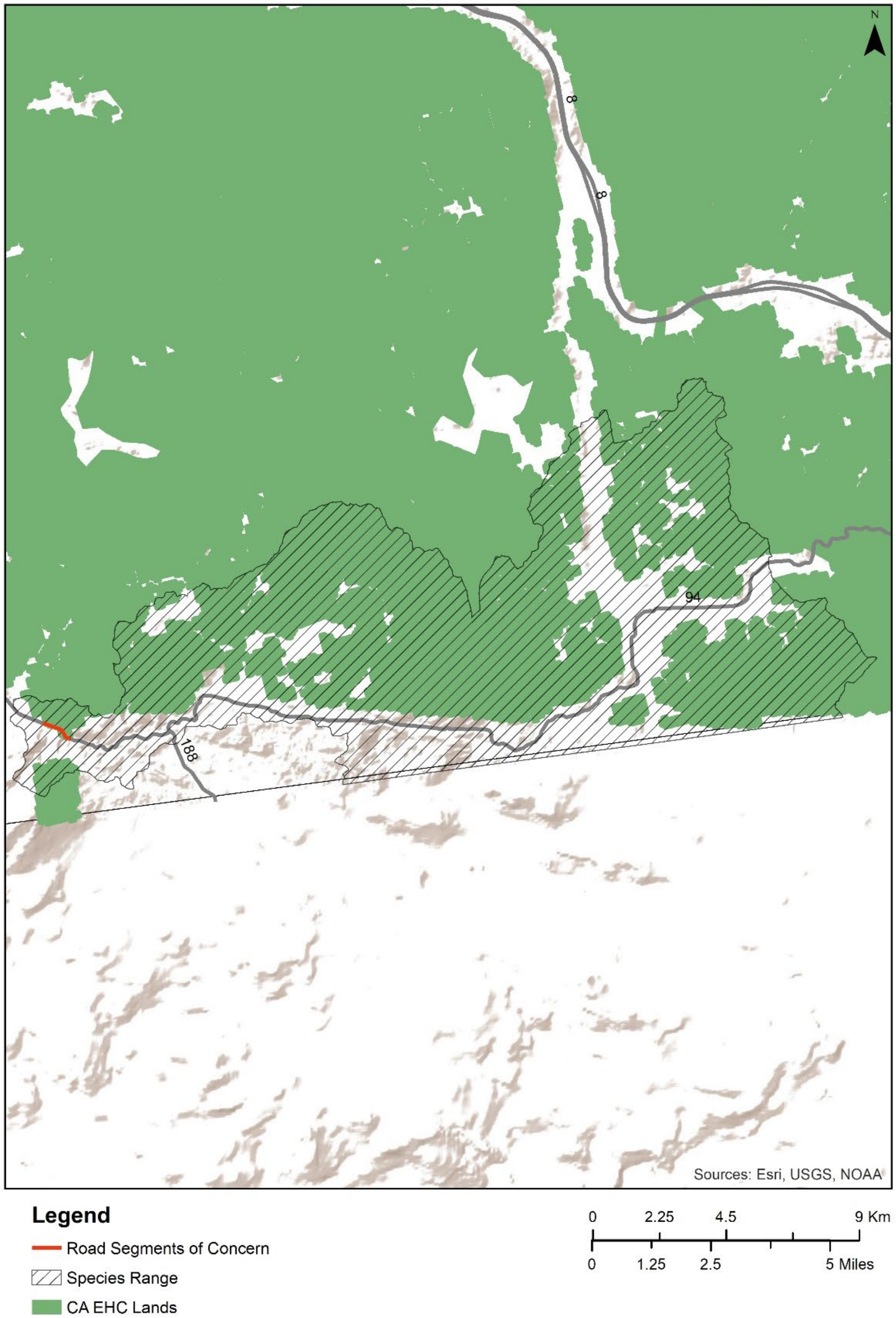

Figure 15. Highway Segments of Concern: Cope's Leopard Lizard (*Gambelia copeii*)

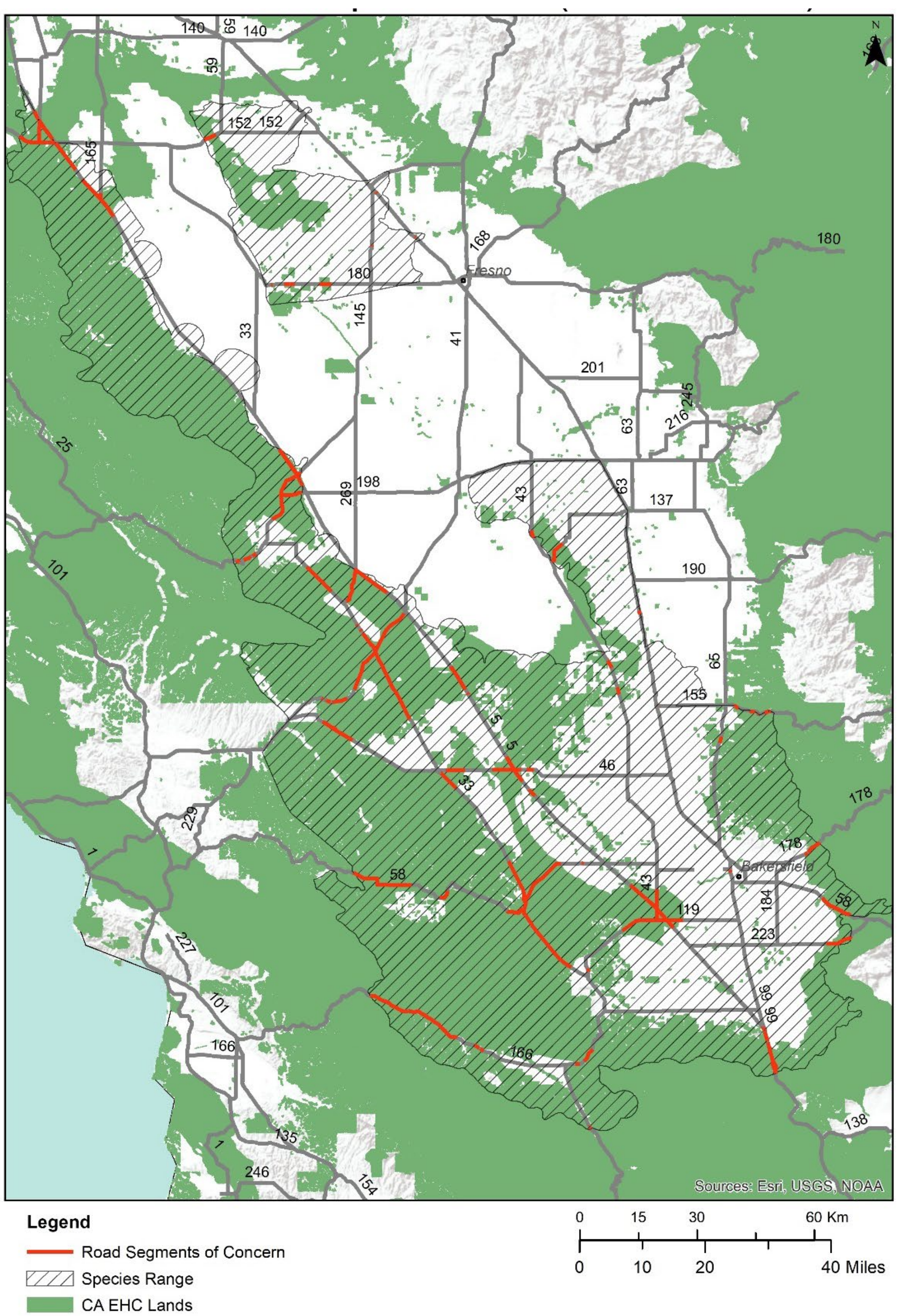

Figure 16. Highway Segments of Concern: Blunt-nosed Leopard Lizard (*Gambelia sila*)

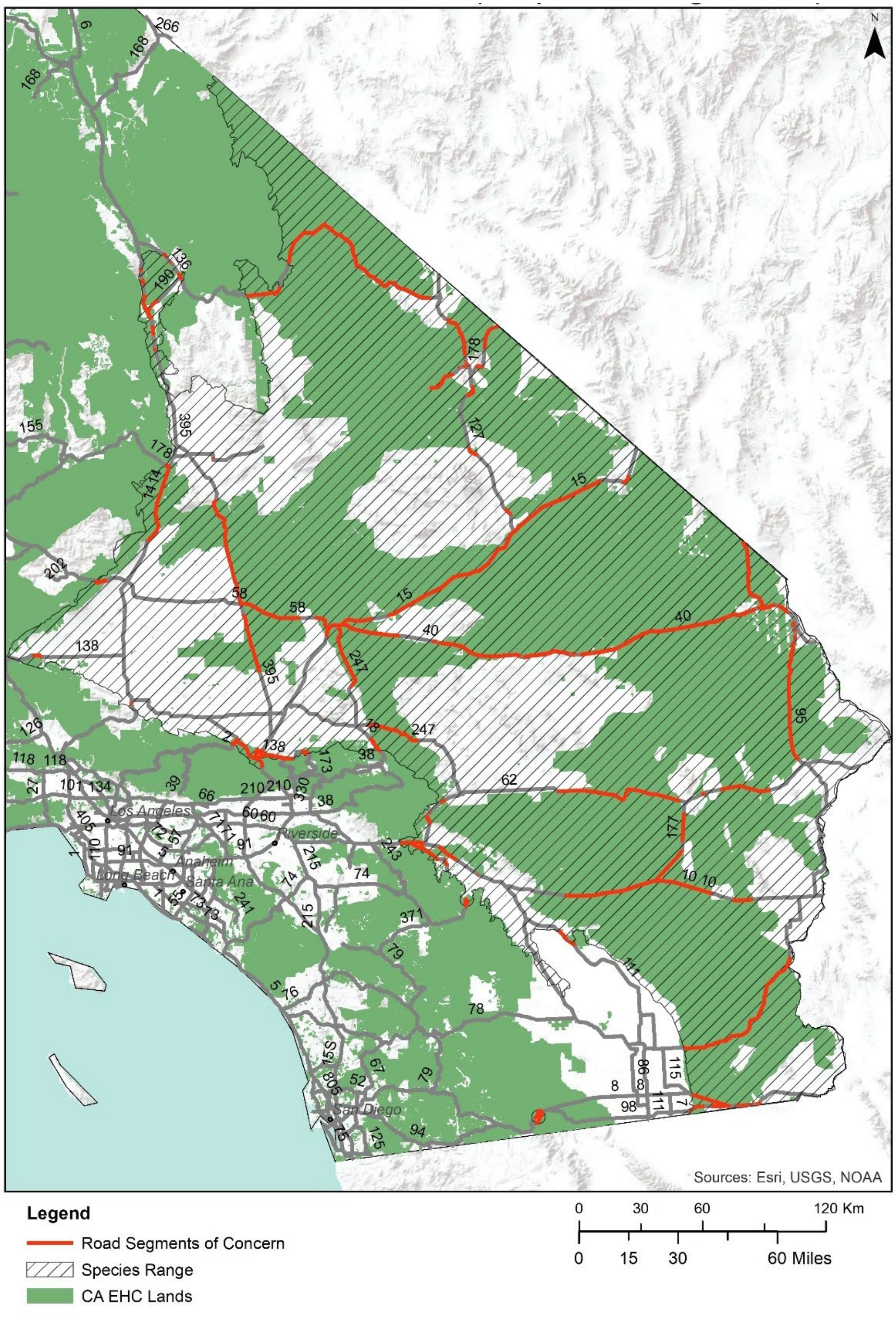

Figure 17. Highway Segments of Concern: Mohave Desert Tortoise (*Gopherus agassizii*)

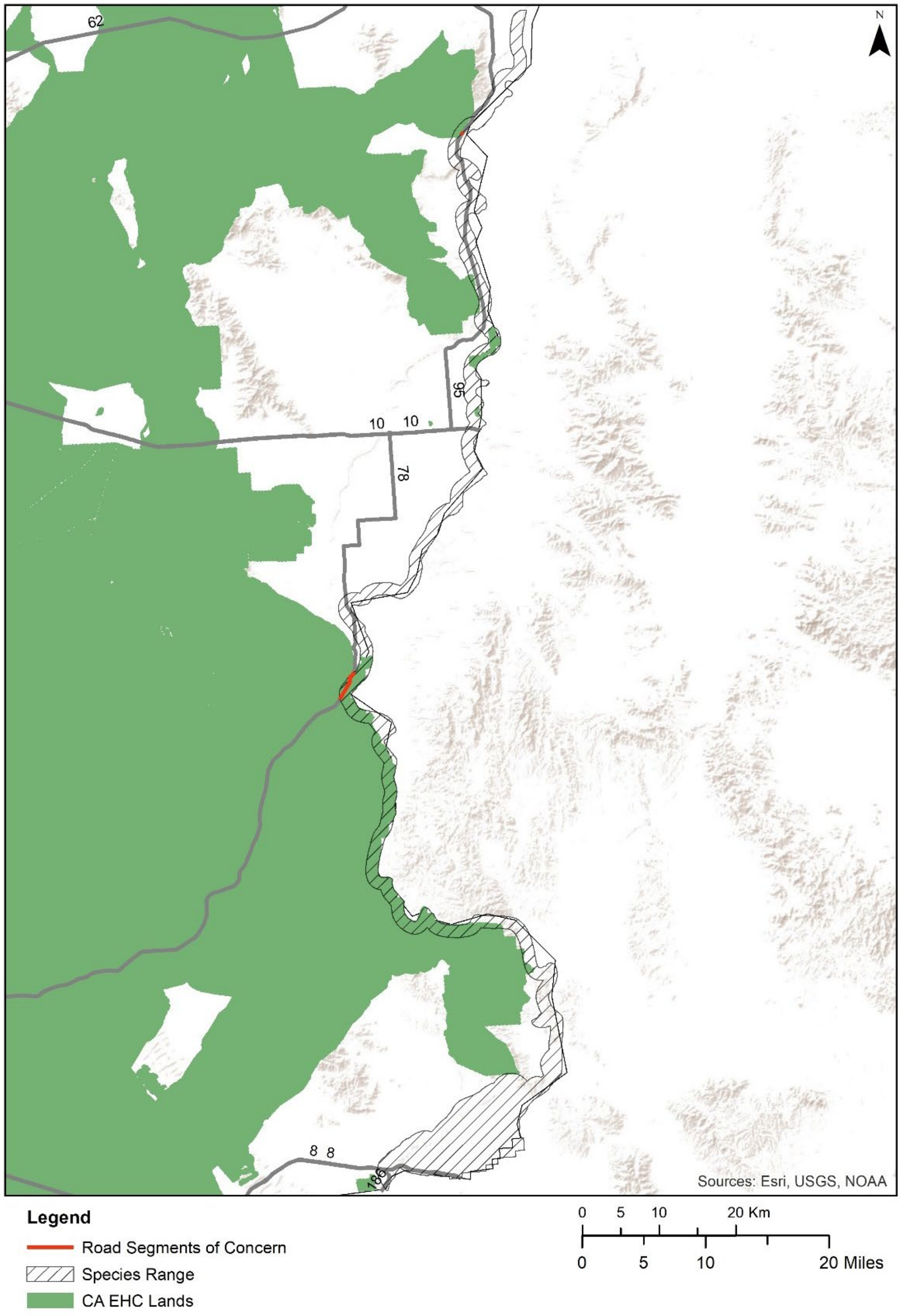

Figure 18. Highway Segments of Concern: Sonoran Desert Toad (*Incilius alvarius)*
Note: Possibly extinct in CA.

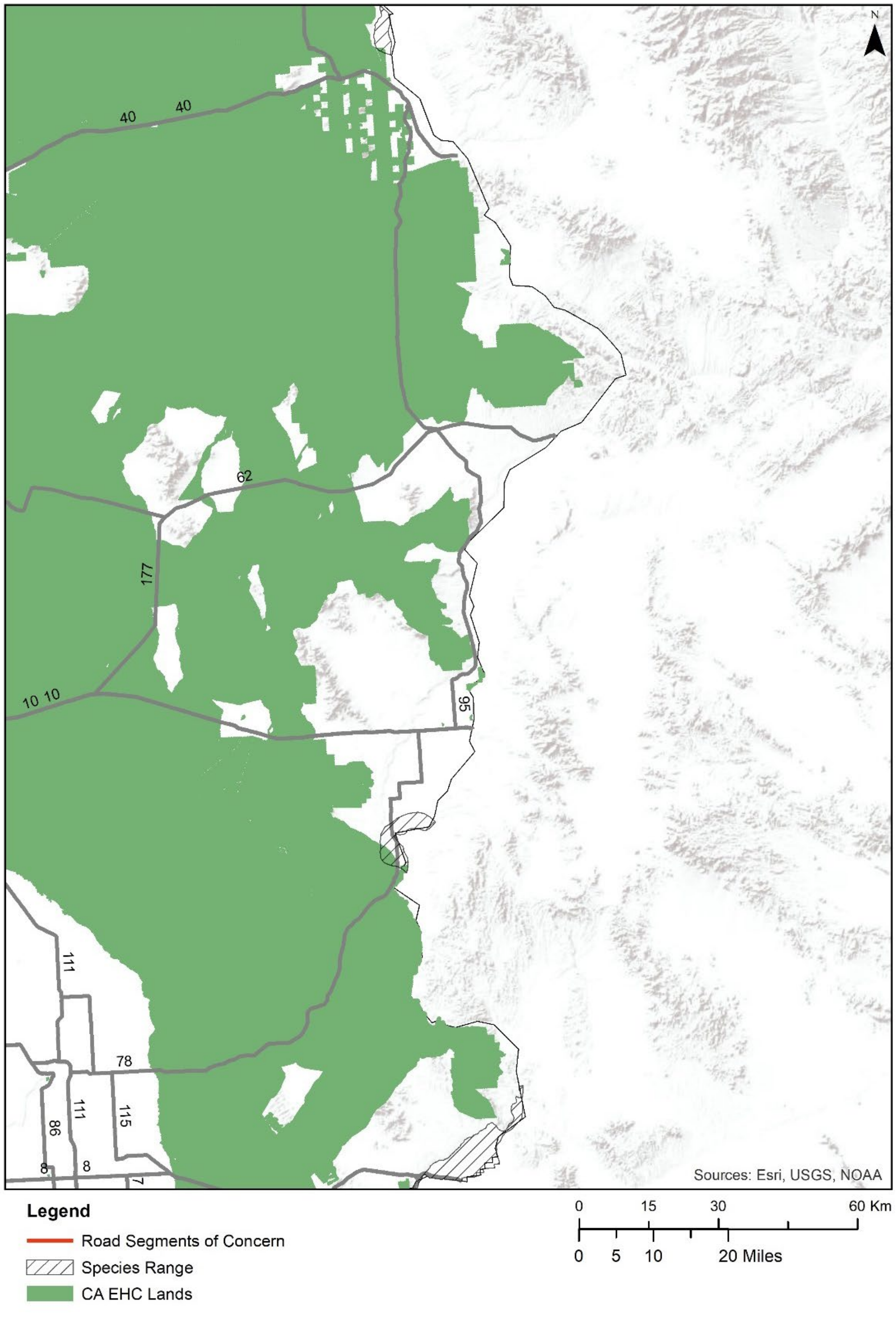

Figure 19. Highway Segments of Concern: Sonoran Mud Turtle (*Kinosternon sonoriense*)

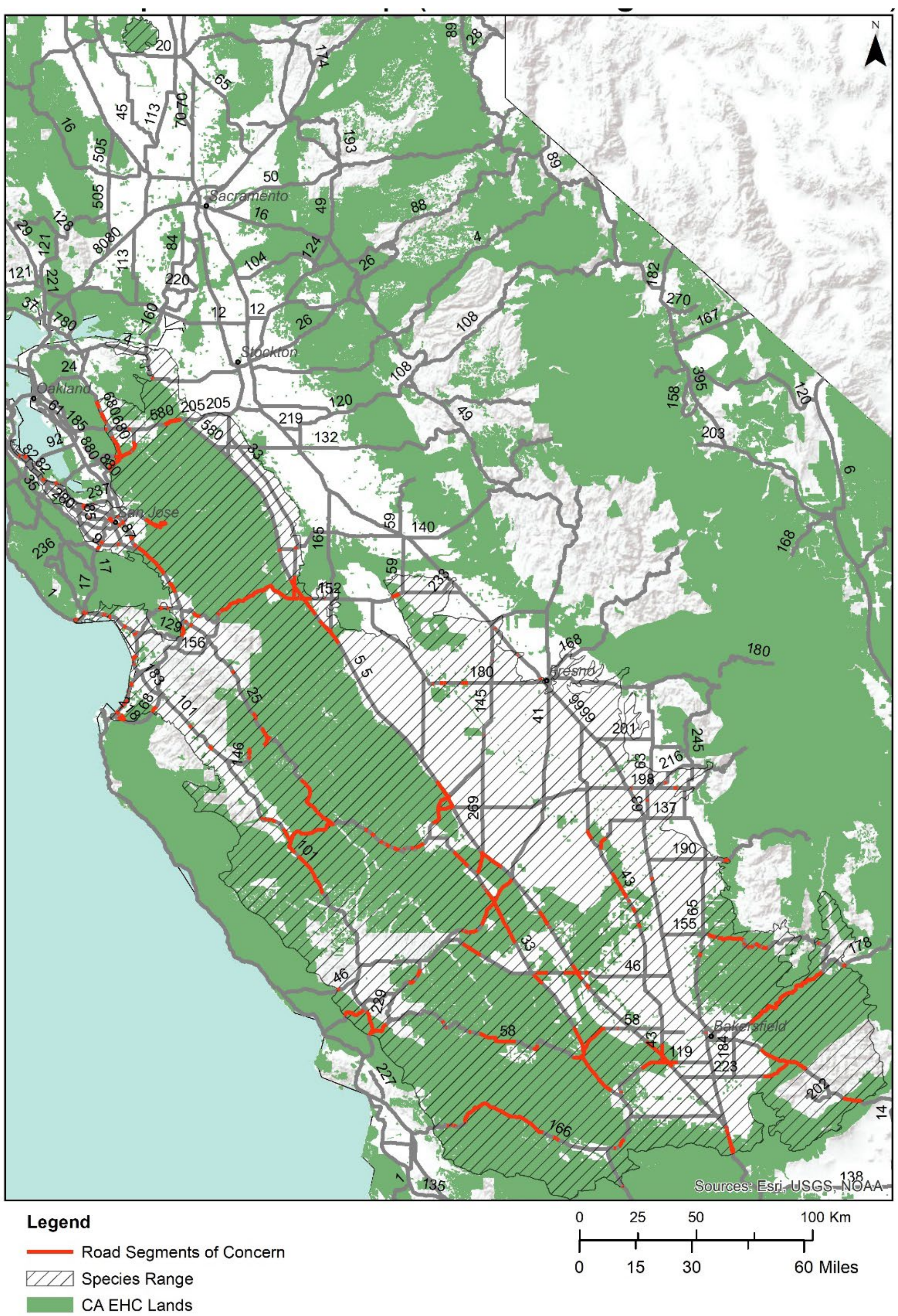

Figure 20. Highway Segments of Concern: San Joaquin Coachwhip (*Masticophis flagellum ruddocki*)

Figure 21. Highway Segments of Concern: Baja California Coachwhip (*Masticophis fuliginosus*)

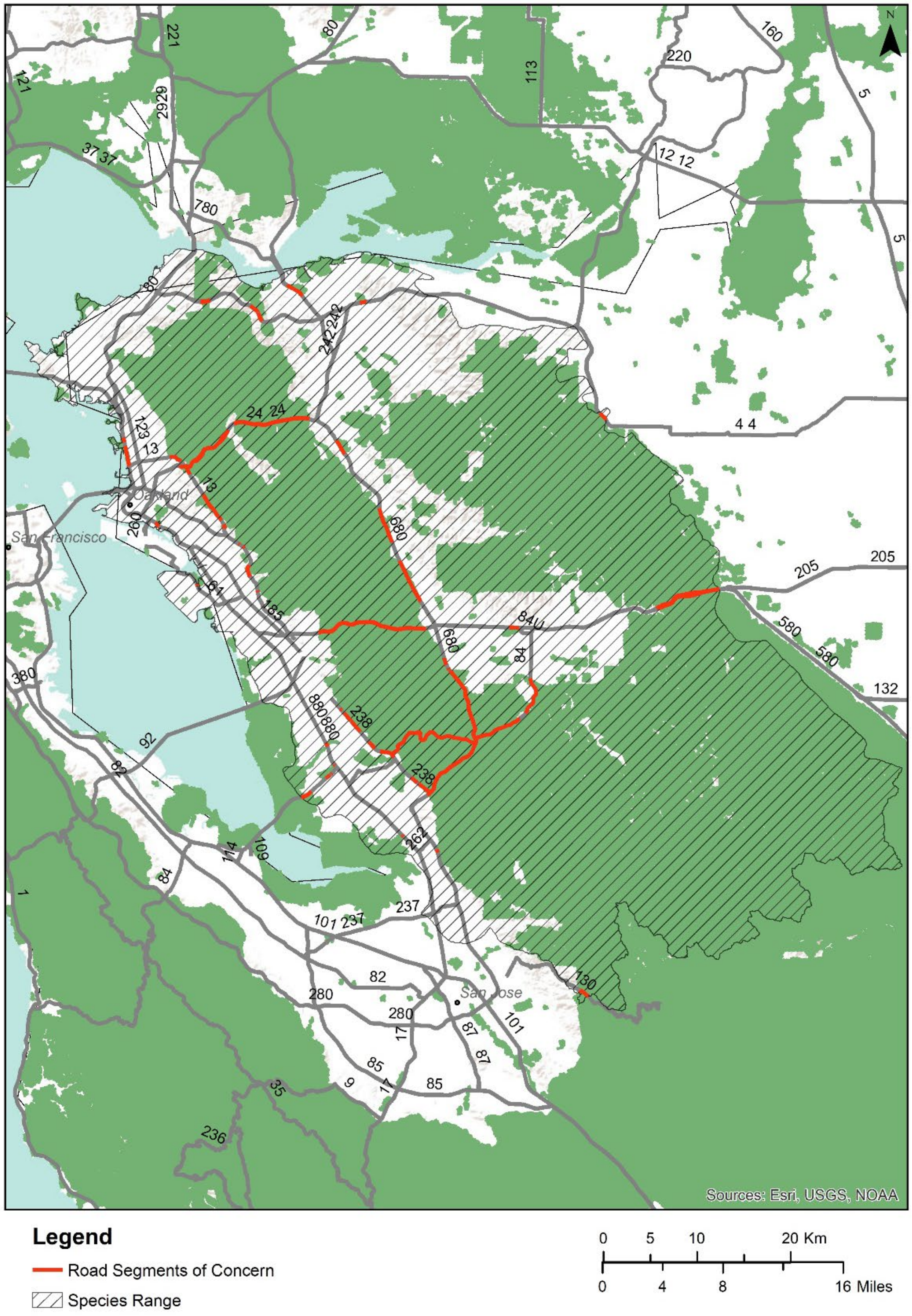

Figure 22. Highway Segments of Concern: Alameda Striped Racer (*Masticophis lateralis euryxanthus*)

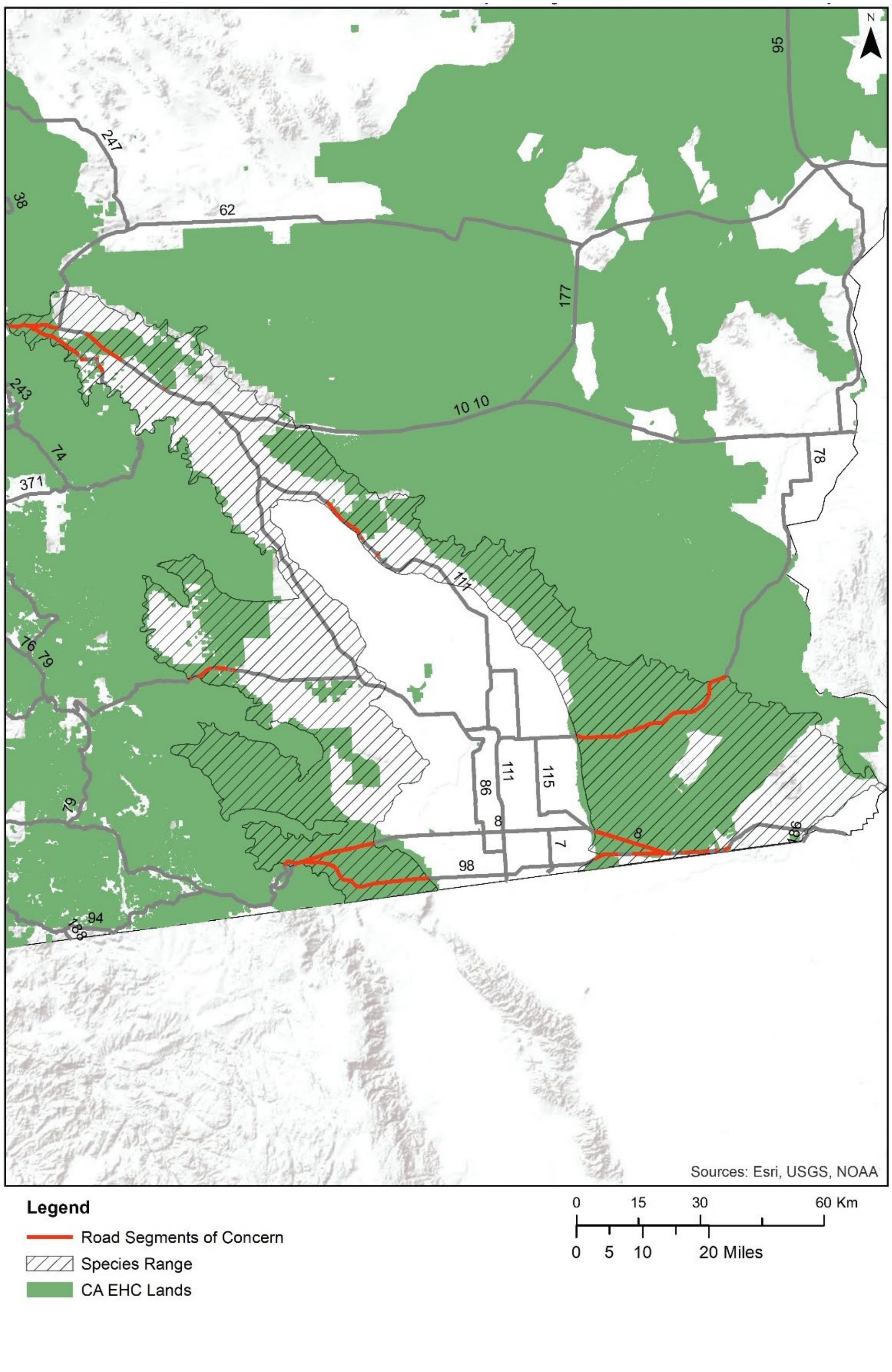

Figure 23. Highway Segments of Concern: Flat-tail Horned Lizard (*Phrynosoma mcallii*)

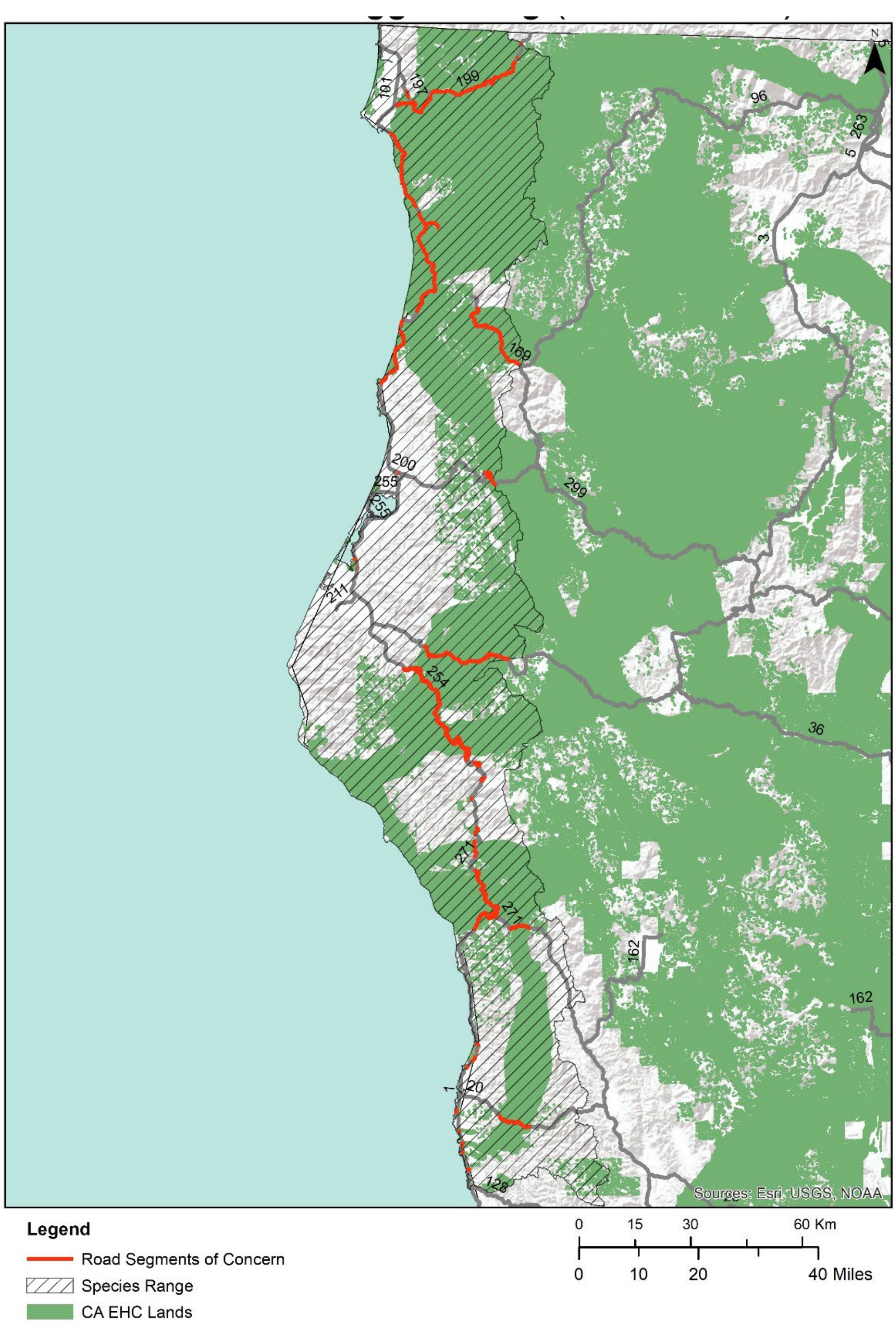

Figure 24. Highway Segments of Concern: Northern Red-legged Frog (*Rana aurora*)

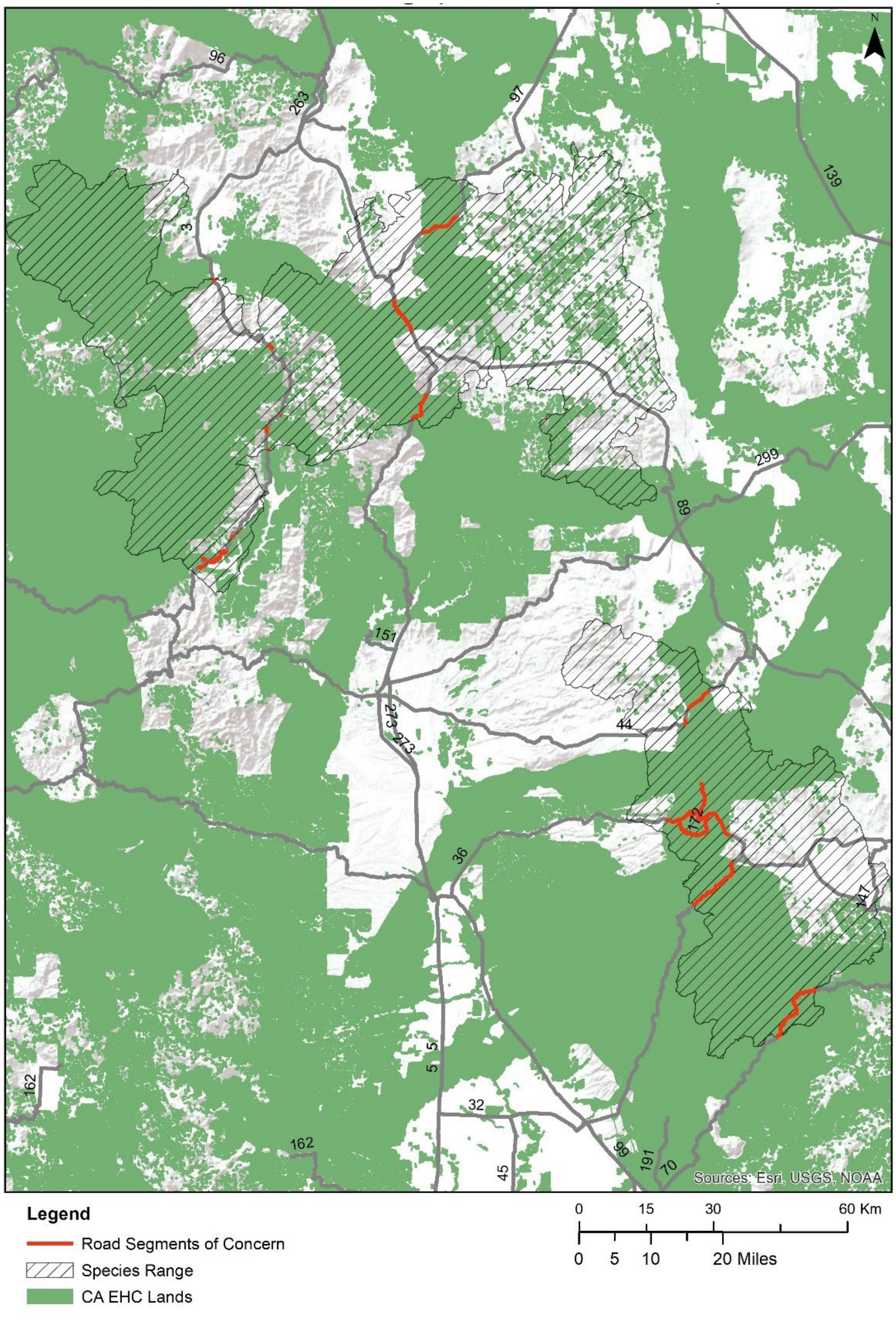

Figure 25. Highway Segments of Concern: Cascades Frog (*Rana cascadae*)

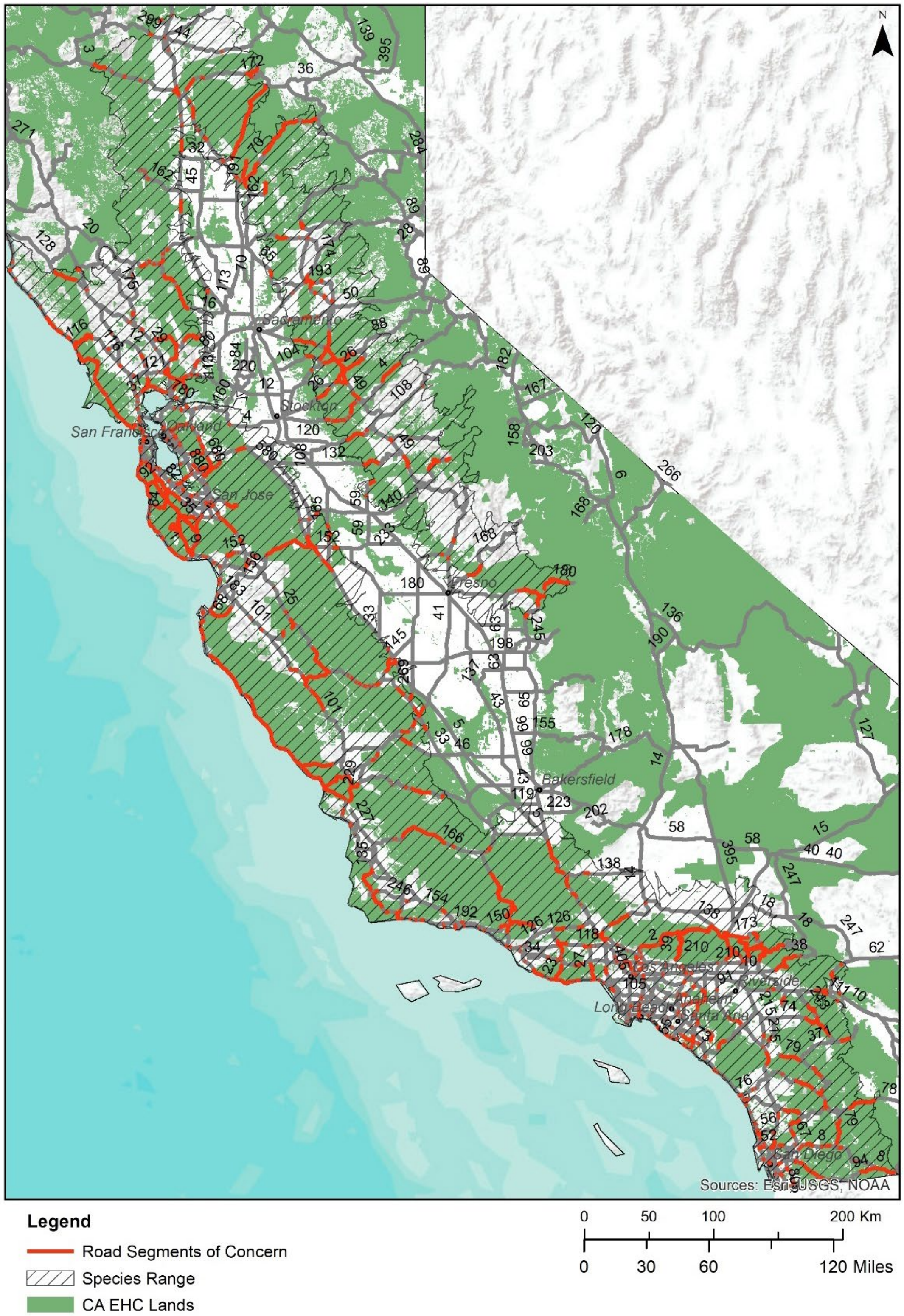

Figure 26. Highway Segments of Concern: California Red-legged Frog (*Rana draytonii*)

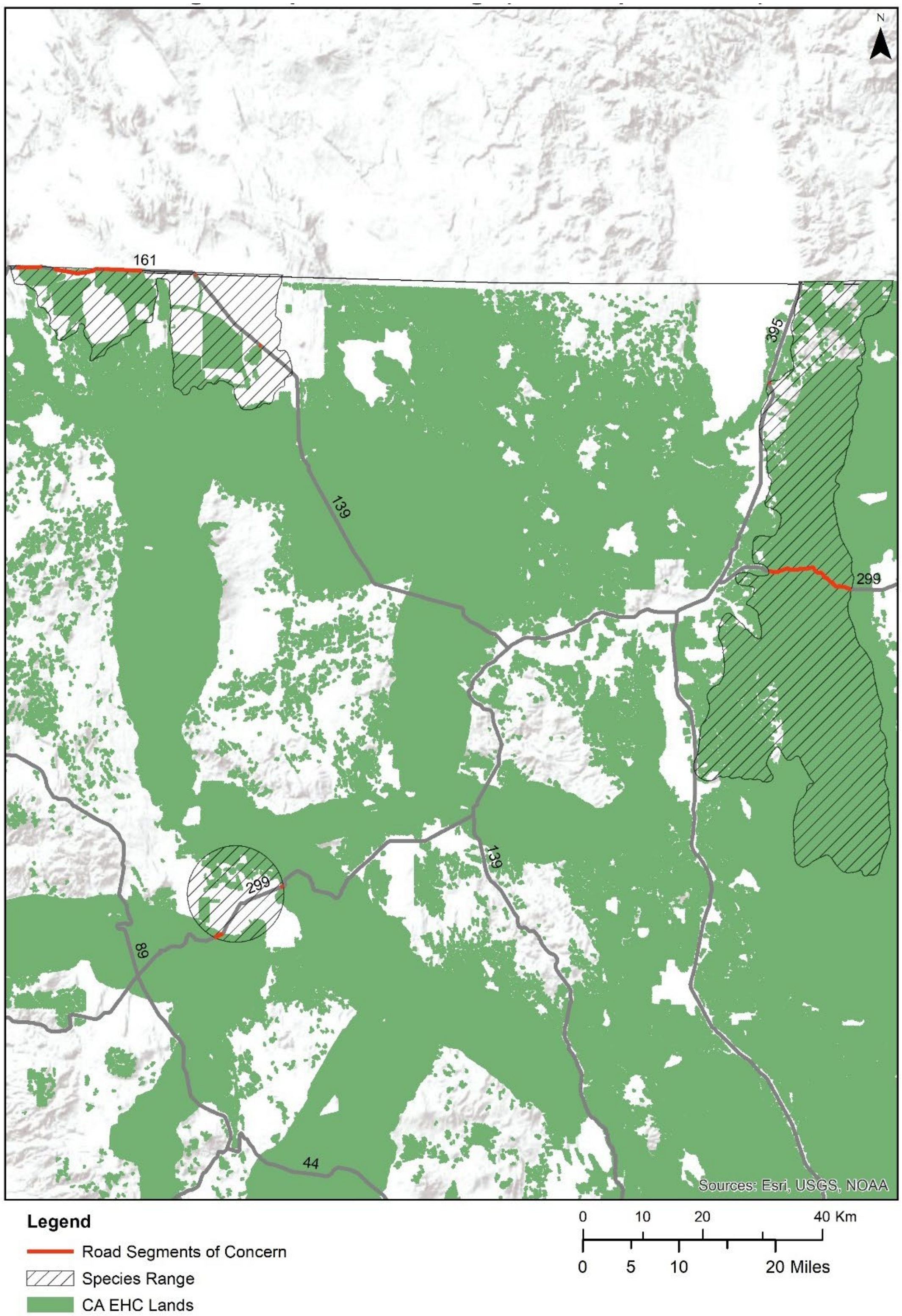

Figure 27. Highway Segments of Concern: Oregon Spotted Frog (*Rana pretiosa*)
Note: Possibly extinct in CA.

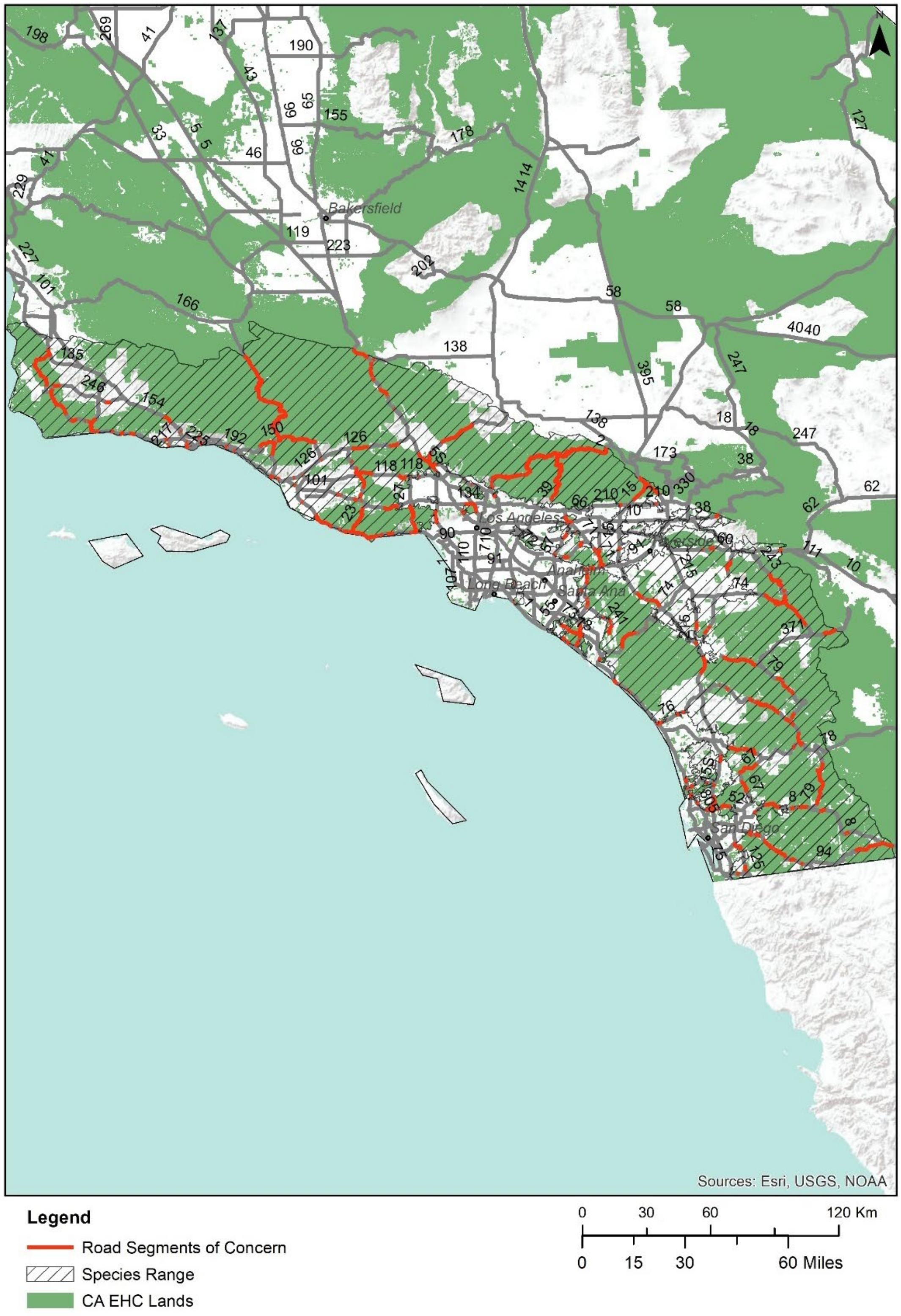

Figure 28. Highway Segments of Concern: Coast Patch-nosed Snake (*Salvadora hexalepis virgultea*)

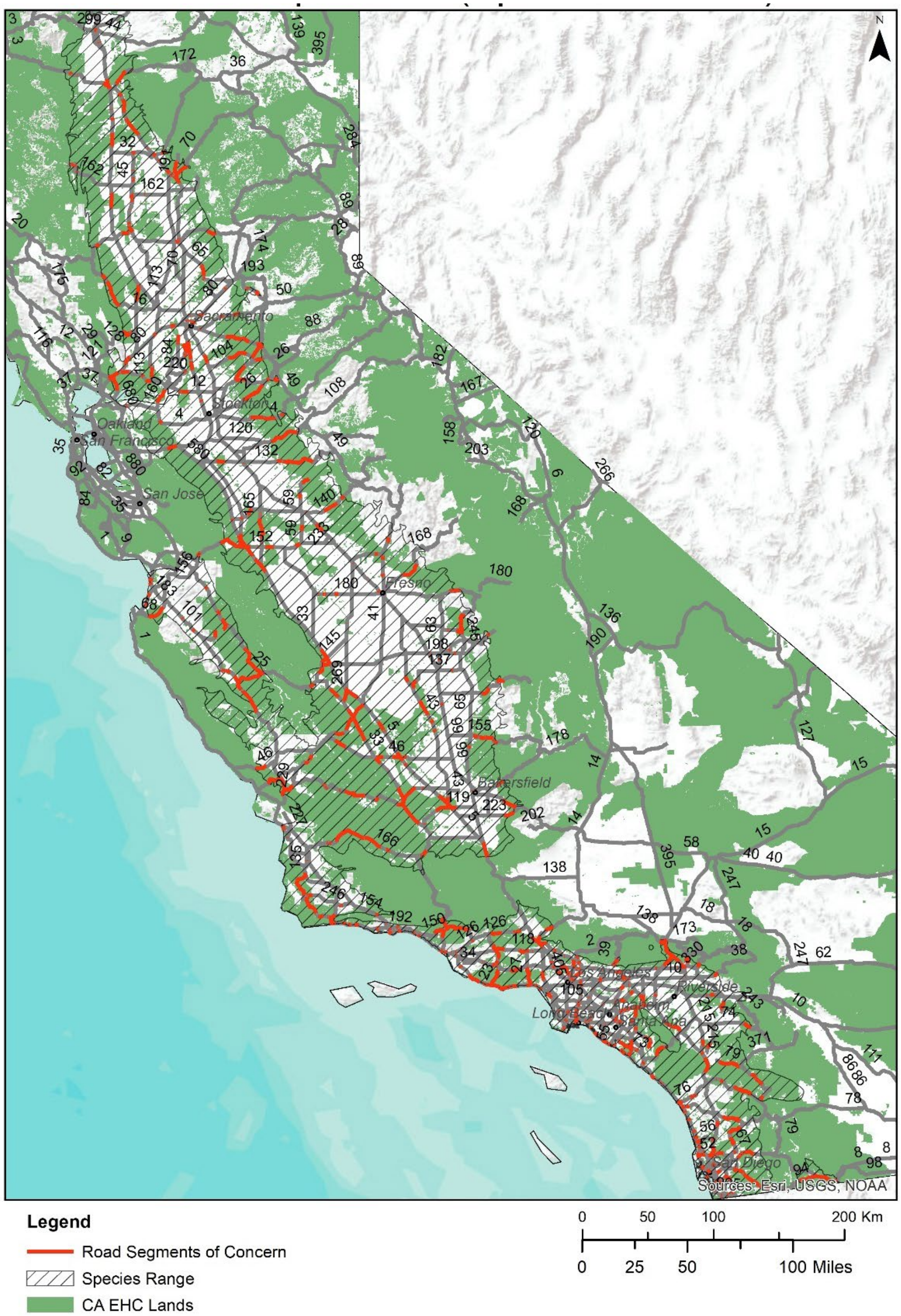

Figure 29. Highway Segments of Concern: Western Spadefoot (*Spea hammondii*)

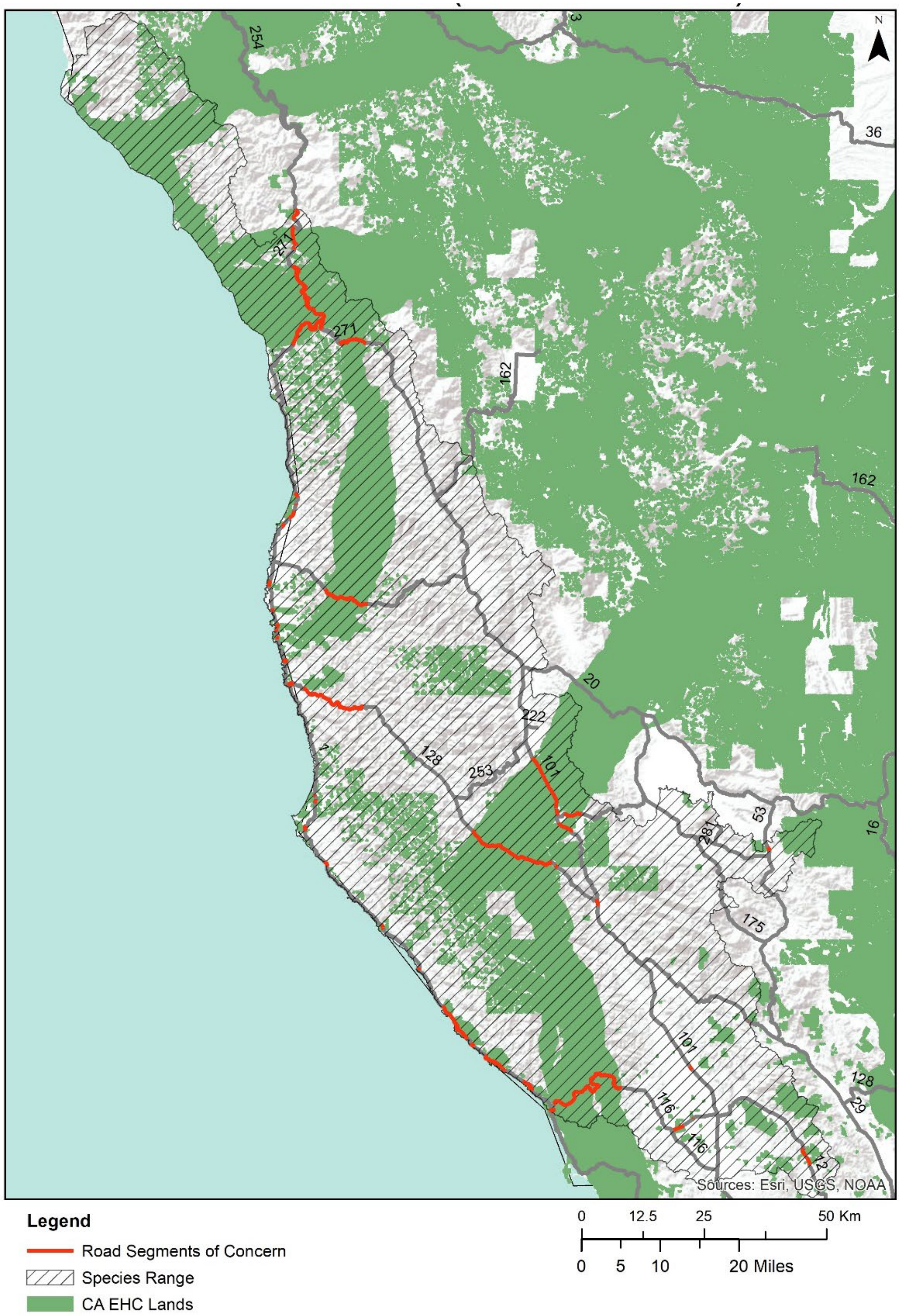

Figure 30. Highway Segments of Concern: Red-bellied Newt (*Taricha rivularis*)

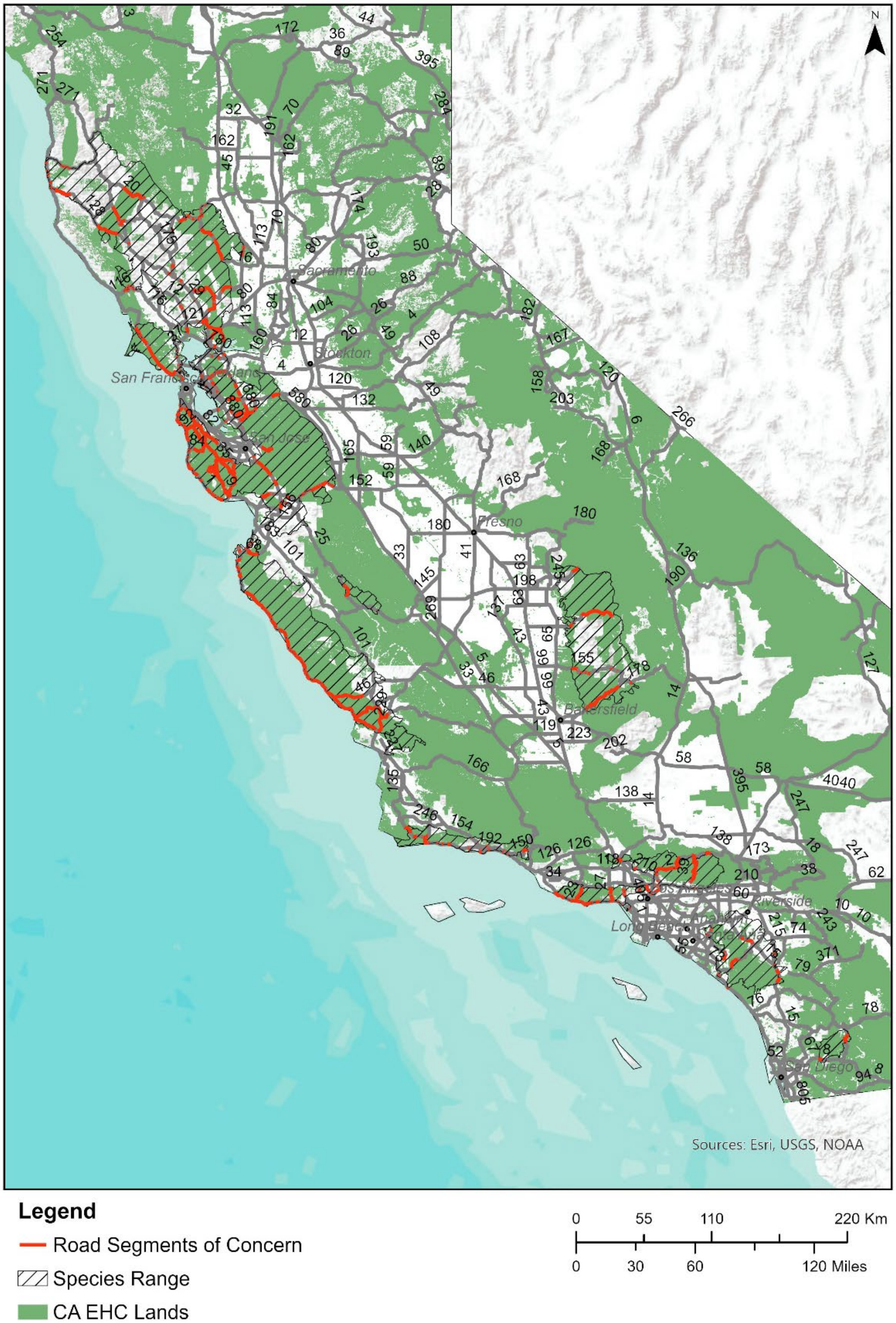

Figure 31. Highway Segments of Concern: Coast Range Newt (*Taricha torosa*)

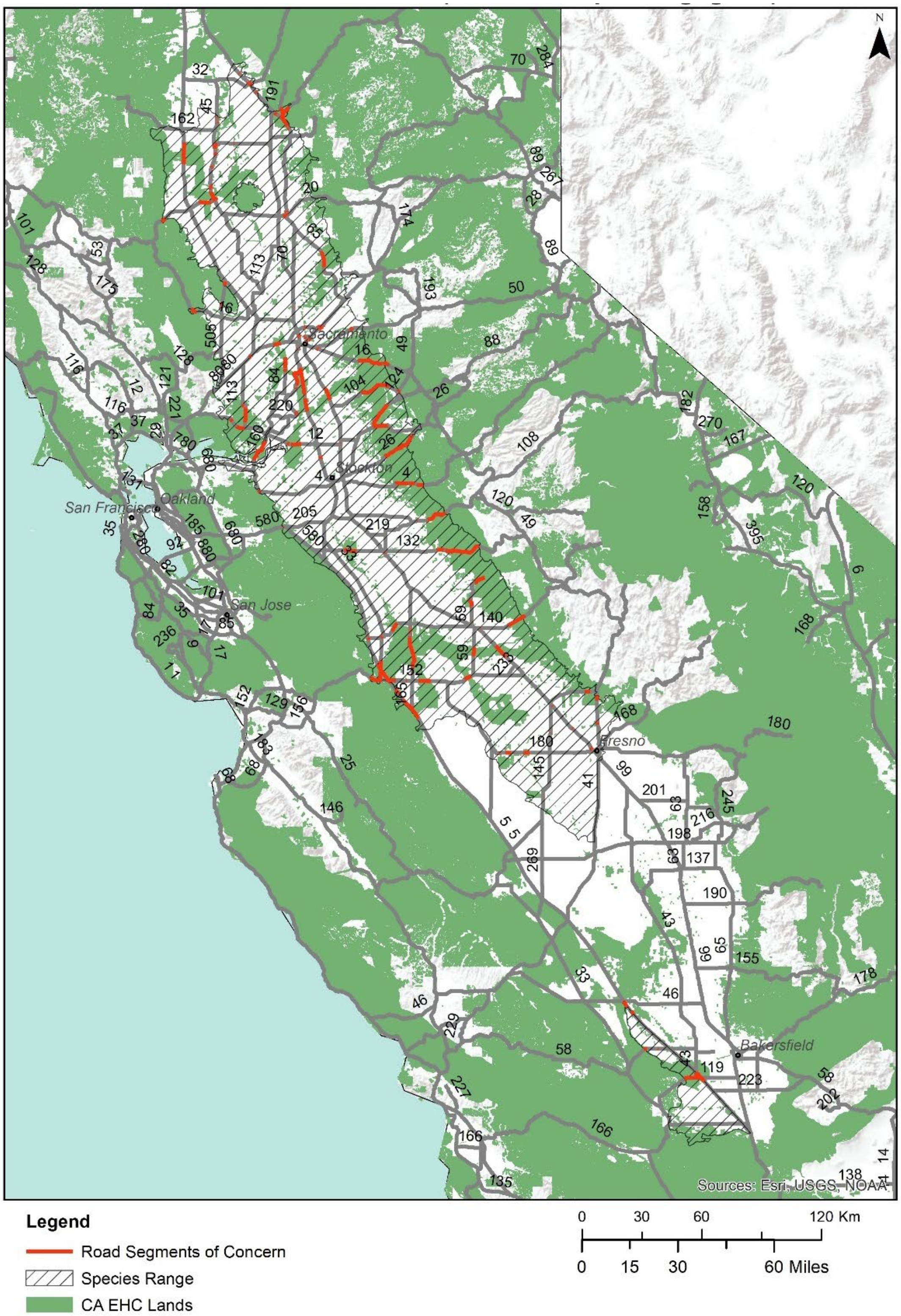

Figure 32. Highway Segments of Concern: Giant Gartersnake (*Thamnophis gigas*)

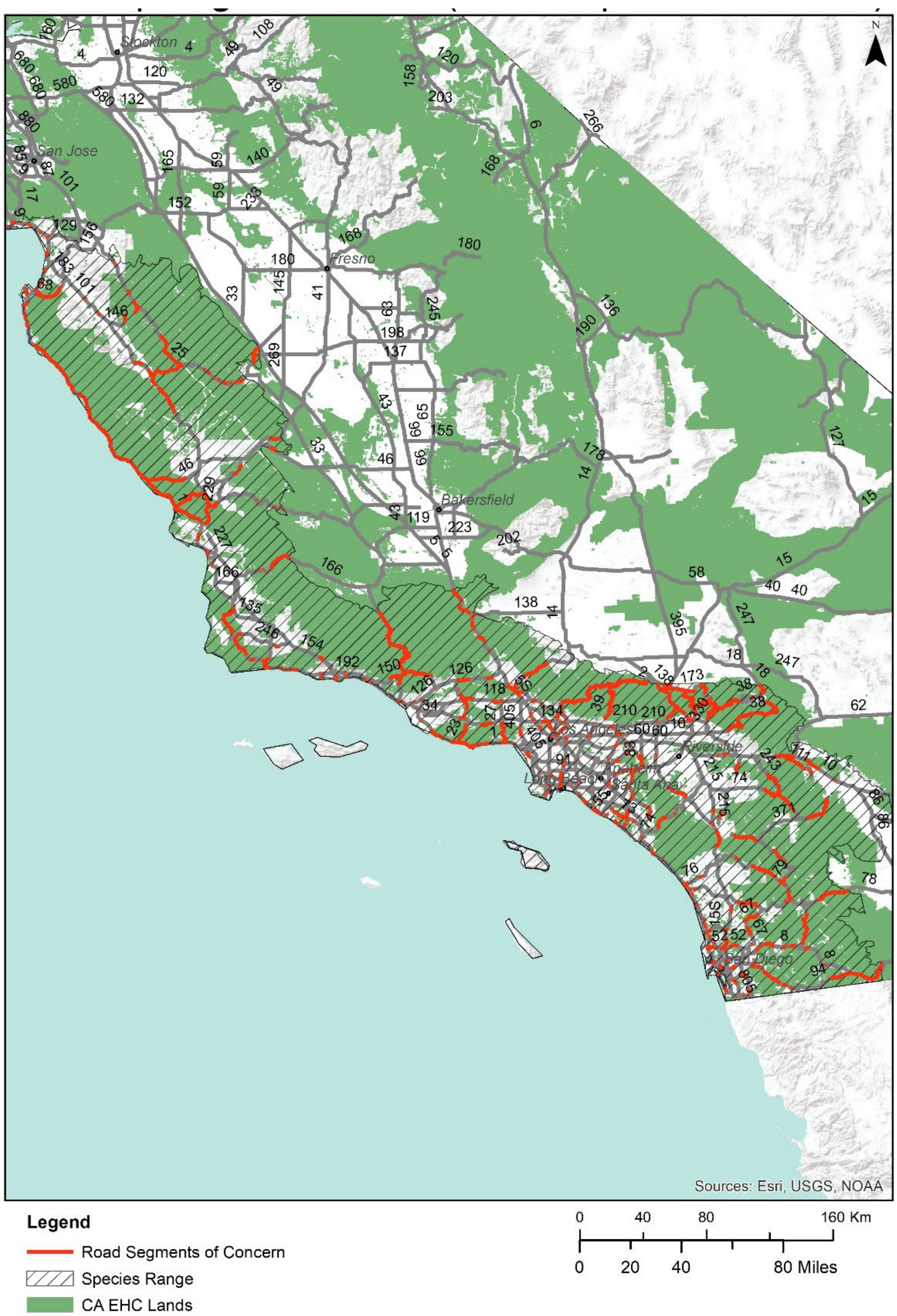

Figure 33. Highway Segments of Concern: Two-striped Gartersnake (*Thamnophis hammondii*)

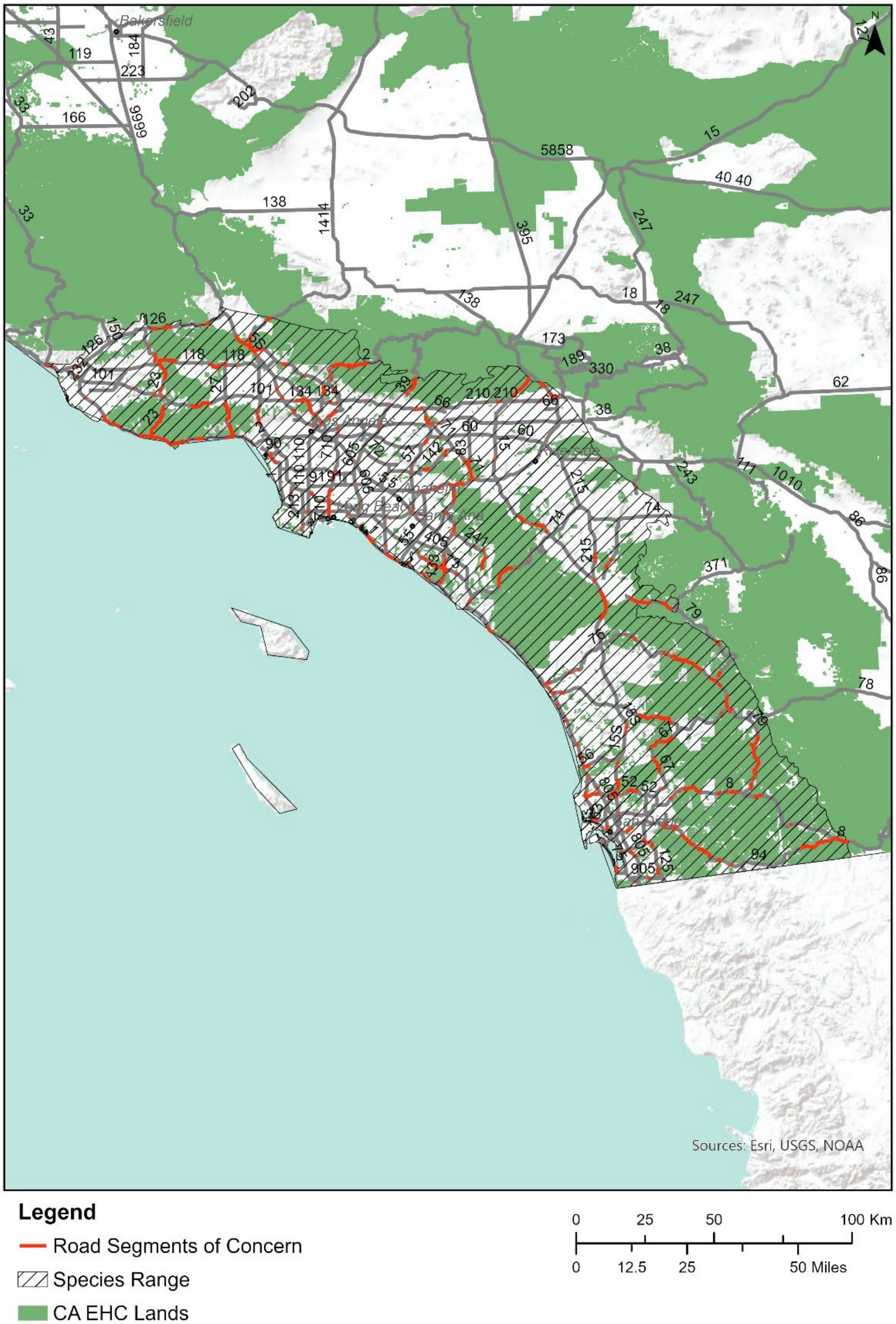

Figure 34. Highway Segments of Concern: California Red-sided Gartersnake (*Thamnophis sirtalis infernalis*)

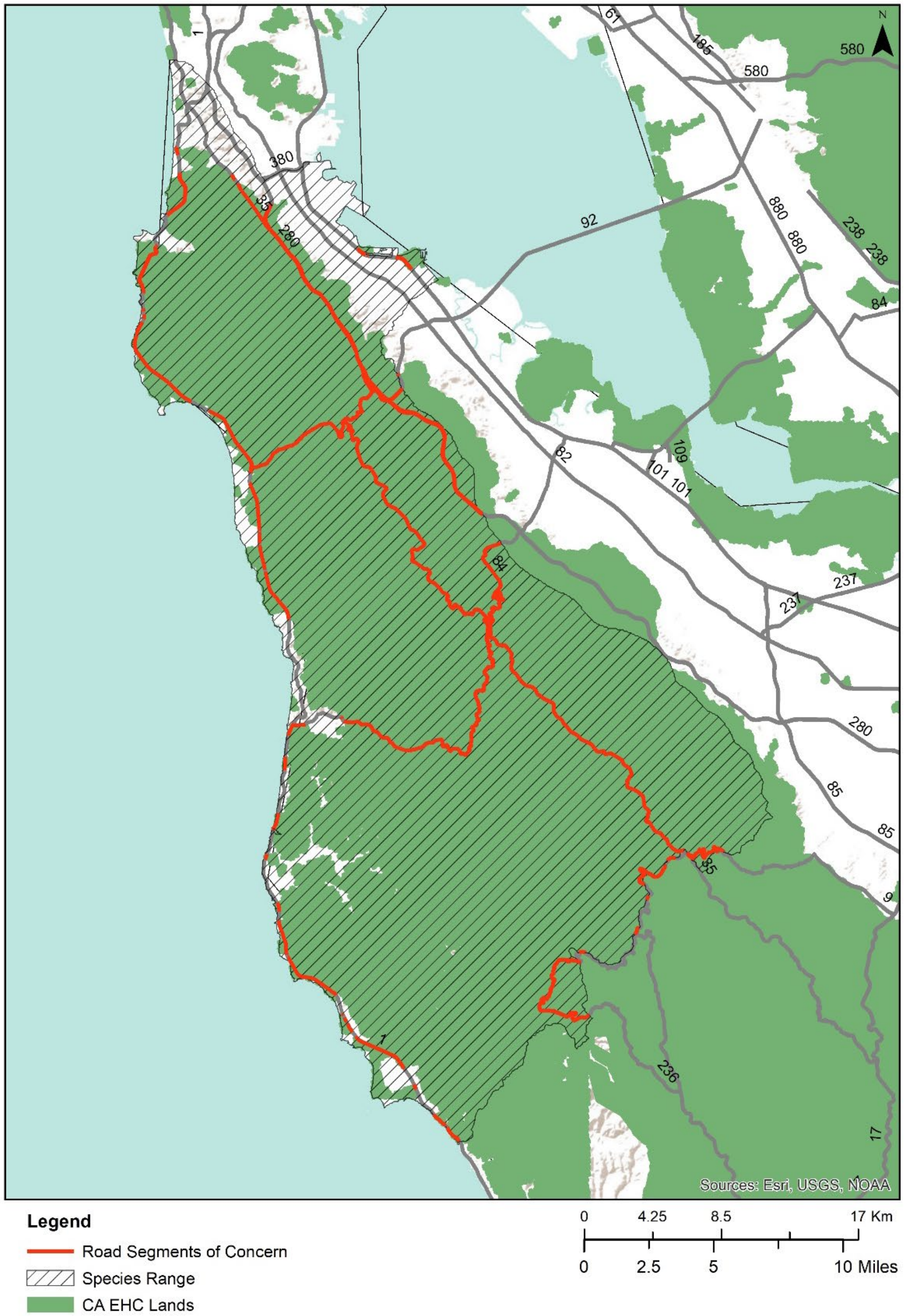

Figure 35. Highway Segments of Concern: San Francisco Gartersnake (*Thamnophis sirtalis tetrataenia*)

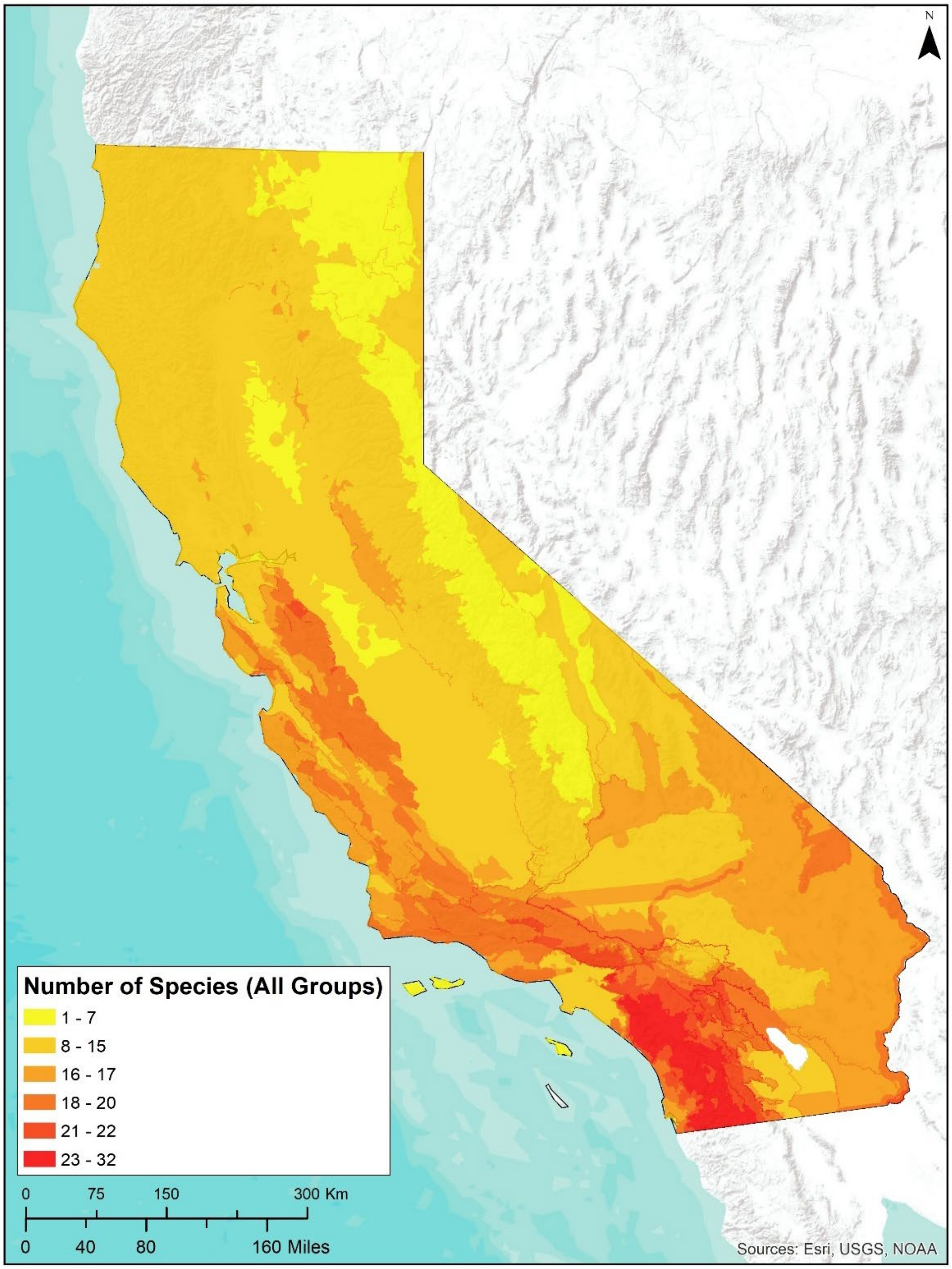

Figure 36. Range Density of Reptiles and Amphibians at High and Very-high Risk of Negative Road Impacts.

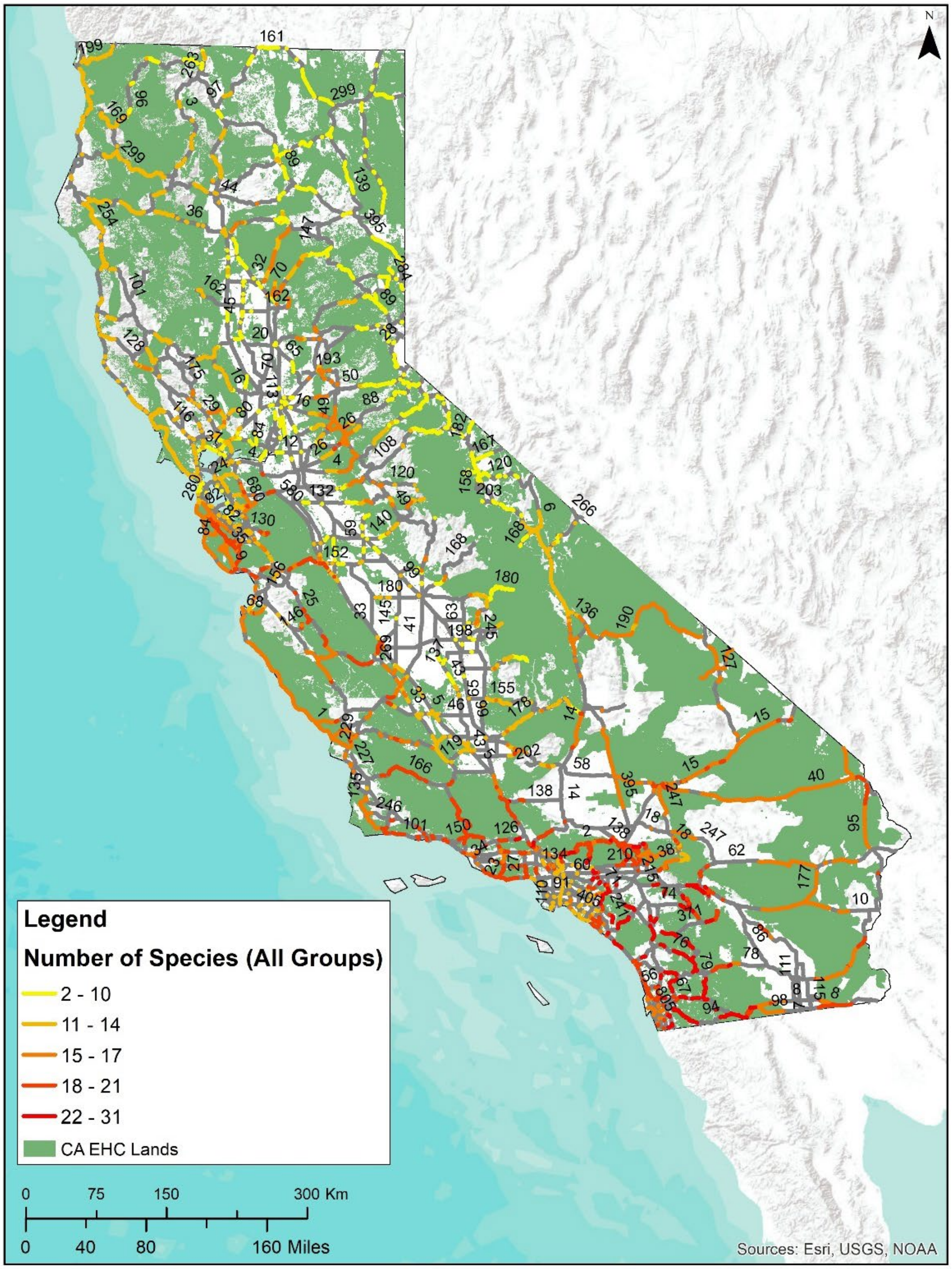

Figure 36. Range Density of Reptiles and Amphibians at High and Very-high Risk of Negative Road Impacts in Relation to California Highways

References

Spencer, WD, P Beier, K Penrod, K Winters, C Paulman, H Rustigian-Romsos, J Strittholt, M Parisi, and A Pettler. 2010. California Essential Habitat Connectivity Project: A Strategy for Conserving a Connected California. Prepared for California Department of Transportation, California Department of Fish and Game, and Federal Highways Administration.

Thomson, RC, AH Wright and NB Shaffer (2016) California amphibian and reptile species of special concern. Univ of California Press.

Chapter 4. Movement of California Tiger Salamanders Along Barrier Fencing and Underpasses in Stanford, CA

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Introduction

Many migratory amphibians make annual population level migrations among breeding wetlands and over-wintering and/or summer foraging upland terrestrial habitats. This requires high levels of connectivity among these habitats (Semlitch 2008, Hamer and McDonnell 2008, Hamer et al. 2015). Because roads often intersect these migratory pathways, all California migratory salamanders, toads and some frogs ranked in the highest risk categories for potential negative road effects, as analyzed by Brehme et al. (2018).

There is substantial evidence that habitat fragmentation and mortality due to roads negatively affect many of these amphibians. For instance, newts regularly migrate long distances over land between breeding ponds and terrestrial foraging habitats (2 km; Trenham 1998). Large numbers are found dead on roads during dispersal periods and newt species are often the first to disappear in fragmented landscapes (Gibbs 1998, Trenham 1998, Shields pers. comm.). Similarly, road mortality and habitat fragmentation are primary threats to the California tiger salamander and other Ambystomid salamanders because terrestrial habitat is used for interpond migration and overwintering (Semlitsch 1998, Trenham et al. 2001, Bolster 2010). There is also evidence that migrating bufonid toads are particularly susceptible to negative impacts from roads (Trenham et al. 2003, Orłowski 2007, Eigenbrod et al. 2008).

To reduce the negative impacts from road mortality on these vulnerable populations, it has been standard practice to build safe crossings in the form of small passages (e.g. culverts, tunnels, etc.) connected by barrier fencing as mitigation. There are a wide variety of small passages and barrier materials that have been constructed with varying degrees of success, although post mitigation monitoring is relatively rare (see review by Langton and Clevenger 2017). The permeability of tunnel systems to amphibian movement may be influenced by openness ratio ((height*width)/length), moisture and temperature conditions within the passage, noise and vibrations, and the correct placement of passages in the landscape (Jochimsen et al. 2004, Hamer et al. 2015, Langton and Clevenger 2017, Helldin and Petrovan 2019).

However, in addition to crossing success within the passage(s), the permeability of crossing systems to amphibian population movements is also dependent upon the proportion of migrating animals that even reach the passage opening. There is evidence that road mitigation systems with inadequate underpass spacing may filter movements of pond breeding amphibians (e.g. Langton 1989, Allaback and Laabs 2002, Pagnucco et al. 2012, Ottburg and van der Grift 2017, Matos et al. 2019). Individuals from a population of the common toad, *Bufo bufo*, in the Netherlands turned around or "gave-up" after an average of 50 m if they did not reach an underpass (Ottburg and van der Grift 2017). The authors considered this the main factor causing a steep population decline in the five years after the tunnel and barrier system was installed. The extent of this potential problem with other mitigation systems and species is largely unknown.

Currently, little science is available in California to inform decisions about the number of crossings and spacing between crossings. Therefore, we studied whether this "giving up" behavior is exhibited in pond breeding amphibians in California, and if so, at what distances different migratory species (and age classes of species) give-up when moving along barrier fencing? This information could inform best management practices for underpass spacing for these species.

There is also some evidence that animals may spend more time trying to climb or interact with transparent fencing compared to solid fencing (Ruby et al. 1994, Milburn-Rodriguez et al. 2016). Therefore, we were interested in whether fencing opacity affects the probability or speed at which CTS and other amphibians find wildlife crossings. Finally, we were also interested in whether 'turnarounds' at fence ends may be effective in altering the trajectory of CTS movement.

We studied a population of California tiger salamanders (CTS: *Ambystoma californiense*) in Stanford, CA to investigate these kinds of behaviors. In this location, a busy two-lane paved road (Juniper Serra Blvd: ave. 17,300 vehicles per day; (City of Menlo Park 2017)) transects upland habitat and Lagunita Lake, a historic CTS breeding site. Large rates of CTS road mortality spurred the construction of a three-tunnel system (5 m apart) in 2003 with approximately 5–10 m of barrier fencing on each side. For our study, we expanded the footprint of existing barrier fencing 150 m in each direction using solid fencing in one direction semi-transparent mesh fencing on the other side.

We addressed the following questions in this study:

1. What is the probability a salamander will reach an underpass based upon the distance from the underpass an animal first encounters the barrier wall?
2. How quickly do CTS travel along the barrier wall toward the underpass?
3. How does the opacity of fencing effect the questions above?
    a. Solid barrier (high-density polyethylene (HDPE-2); Animex®)
    b. Semi-transparent barrier (water- permeable rigid polymer matrix; ERTEC® E-Fence, referred to hereon as "mesh")
4. Are fence end 'turnarounds' effective in redirecting the trajectory of CTS movement?
5. Once CTS reach the tunnels, what is the permeability of the road crossing tunnel system to CTS passage?

Methods

Field Study

We studied the movement of CTS adjacent to three existing underpasses along Junipero Serra Blvd. in Stanford, CA (Stanford University) in the winter breeding seasons of 2017/18 and 2018/19. The road bisects a historic CTS breeding pond (Lake Lagunita) and upland CTS habitat (Figure 1).

Figure 1. Map of Barrier and Tunnel Study System at Stanford University Between Upland and Breeding Habitat for CTS.

A total of 300 m of barrier fencing was installed along the south side of Juniper Serra Blvd. (150 m in each direction); the new fencing was connected to 5 m of existing barrier fencing adjacent to three salamander tunnels (ACO Wildlife ®). The tunnels, installed in 2003, are 14 m in length and spaced 5 m apart. One portion of the fencing installed was semi-transparent mesh (ERTEC ® rigid polymer matrix) and the other portion was solid (Animex ® high-density polyethylene (HDPE-2)). To minimize potential for vandalism, the fencing was placed within existing security fencing present on site. Jump-outs (ERTEC® cones and high berms) were installed a minimum of every 25 m along the fence to provide CTS and other small vertebrates a way to get back into the habitat if they ended up on the roadside of the barrier fencing. At outer fence ends, turnarounds were installed to redirect animals away from the road and back toward the upland habitat in a U-shaped fashion. The turnarounds were approximately 2 m long and 1 m in width. Fencing was installed with the bottom buried in the ground according to manufacturers' guidelines.

HALT ® camera systems (Hobbs and Brehme 2017) were placed every 25 m along the new fence lines from 0 to 125 m from the existing tunnel system (Figure 2). Each 0 m camera was approximately 5–8 m from the closest tunnel opening where our newly installed fencing intersected with the existing barrier fencing.

At fence end turnarounds, HALT camera systems were placed above the fence end at the turn-around to record video of animals' movement trajectory after coming out of the turn-around. Due to evidence of CTS turning around but not being recorded on video, in 2019, we narrowed the terminal end of the turnaround from 1 m to approximately 0.35 m from the main fence creating a tear drop shape. This allowed us to install the HALT trigger at the turnaround opening so that we could record animals entering and exiting the turnaround. In 2019, we also placed these camera systems within each tunnel opening and exit to record tunnel permeability. Cameras were set whenever rain was predicted and checked on a weekly basis during the winter adult migration season from the uplands toward the pond (Nov.–Feb.). Each time we set and checked the cameras, we took a photo of a battery powered atomic clock in order to calibrate exact minutes and seconds upon processing. All work was performed under Stanford University Habitat Conservation Plan (Federal incidental take permit # TE182827-0) and California State Consistency Determination (2080-2016-001-03)

A) B) C)

Figure2. Solid (A) and Mesh (B) Fence Lines with Cameras Within Wood Structures and Plastic Bins Facing Down Toward HALT Triggers. Fencing Leads to a Series of 3 Tunnels Under the Roadway (C).

Analysis

Photos of all CTS were analyzed using pattern recognition software to identify individuals by their unique spot patterns (I^3S Spot; Van Tienhoven et al. 2007; Figure 3). Camera location, time, and direction of movement were recorded for each individual. Snout to vent length was measured with Program ImageJ (Rasband 1997–2018) using the 1 cm grids from the HALT trigger for calibration.

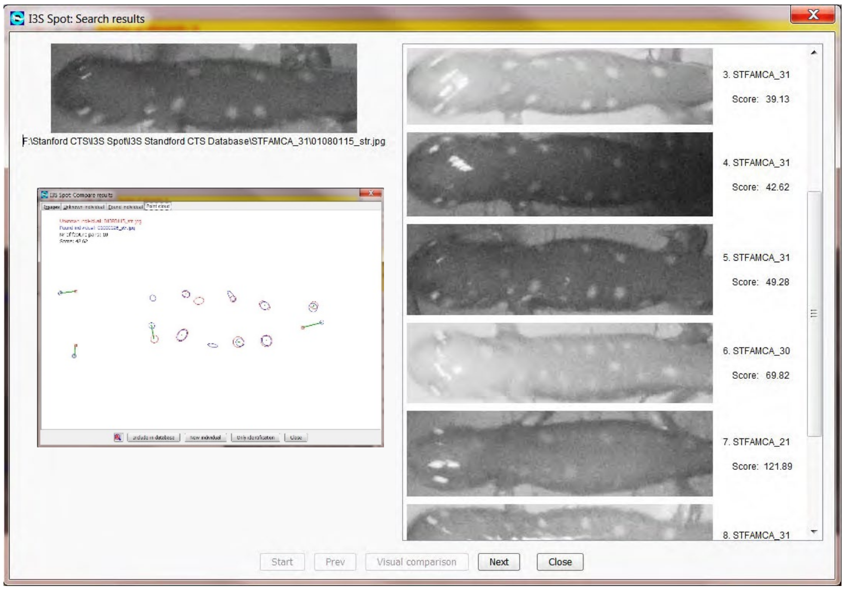

Figure 3. Example of CTS Identified to Individual Using I^3S Software to Distinguish Spot Patterns (top 3 on right are same individual)

For individual CTS, we then calculated movement distances along the fence lines, numbers of turn arounds, speed, and "success" at reaching 0 m cameras next to underpass system. Because cameras were placed 25 m apart, our margin of error for estimating fence movement distance ranged between 0 and 25 m. For instance, if an animal was only detected at a single camera between 25 m and 125m, then our average estimated distance was 25 m (12.5 m before reaching the camera and 12.5 m after exiting the camera). Similarly, if an individual was detected at multiple consecutive cameras moving in the same direction, our margin of error was typically 25 m. In the instances where individuals were detected at consecutive cameras, we also calculated the movement speed between segments. If such an individual then turned around and was re-detected at a camera while moving in the other direction, we were able to estimate the distance travelled along the fence before turning around by multiplying the time between detections by its average speed. Because of this, if individuals travelled back and forth several times, we were able to more accurately estimate the total distance of fence line traversed (fence movement distance). If an individual reached the 0 m camera (where the experimental fence lines attached to the short length of existing fence), this was considered a "success" at reaching the passage system with no added error for distance moved afterward.

We used Markov Chain Monte Carlo (MCMC) implemented in the R programming language and the runjags package (Denwood 2016) to interface with JAGS (Just Another Gibbs Sampler) to sample values of all unknown parameters from the joint posterior distribution. In each case, four chains were sampled to perform standard diagnostics for convergence. In all cases, non-informative prior distributions were used for all parameters.

Logistic Regression for Success in Reaching Underpass Opening

We modeled the probability of success of CTS in reaching the 0 m camera near the crossing opening. For this, we used a Bayesian approach to logistic regression modeling (Congdon 2006; Figure 4). The response was a Bernoulli random variable, where 0 indicates failure and 1 indicates success in being detected by the camera at the opening of the crossing (ReachedTunnel). The probability of success for the Bernoulli distribution is a logistic (i.e. p = exp(y)/(1 + exp(y)) function of the linear component of the model that consists of four predictors (FenceType, InitLoc, InitAway, InitLocAway) and five parameters that include an intercept and a regression coefficient corresponding to each of the predictors. FenceType is a binary variable where 0 indicates a mesh fence and 1 indicates a solid fence. InitLoc is the position along the fence where the animal was first detected in meters from the crossing opening (with error described in the previous paragraph), InitAway is a binary variable where 0 indicates that the animal was initially moving toward the crossing and 1 indicates it was initially moving away from the crossing, and InitLocAway is an interaction (product of) InitLoc and InitAway. All predictors were standardized (the mean subtracted from each value and then divided by the standard deviation) prior to modeling. The priors for the parameters were non-informative normal distributions with mean 0 and 0.001 precision (i.e. a variance of 1000). The parameters were sampled from their posterior distributions using MCMC (as described above) and described by mean, median, and quantiles of their marginal distributions. This allowed us to assess the effect of each predictor on the probability of success.

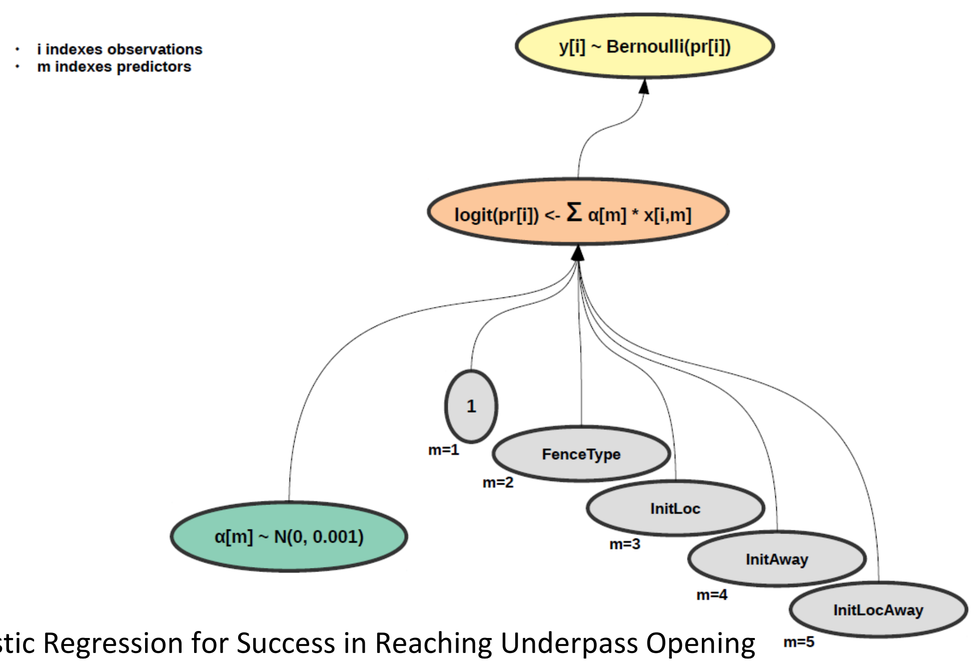

Figure 4. Logistic Regression for Success in Reaching Underpass Opening

Gamma Regression for Distance Moved Along Fence

We also modeled the distance that CTS moved along the fence. We used a Bayesian approach to regression modeling of the probability of successfully reaching the underpass opening (Figure 5). The response was assumed to be a gamma distributed random variable, which is a continuous positive variable representing the distance the animal moved along the fence as described. The gamma distribution has a shape parameter, which we assumed to be independent of any predictors, and a rate parameter that we model as an exponential (i.e. rate = exp(y)) function of the linear component of the model that consists of four predictors FenceType, InitLoc, InitAway, ReachedTunnel, InitLocAway and six parameters that include an intercept and a regression coefficient corresponding to each of the predictors. All predictors, except for ReachedTunnel, were standardized prior to modeling. The prior for the shape parameter was a non-informative exponential distribution with a rate of 0.00001. The priors for the regression parameters for the rate were normal distributions with mean 0 and 0.001 precision (i.e. a variance of 1000). The parameters were sampled from their posterior distributions using MCMC (as described above) and described by mean, median, and quantiles of their marginal distributions. This allowed us to assess the effect of each predictor on the distance moved along the fence.

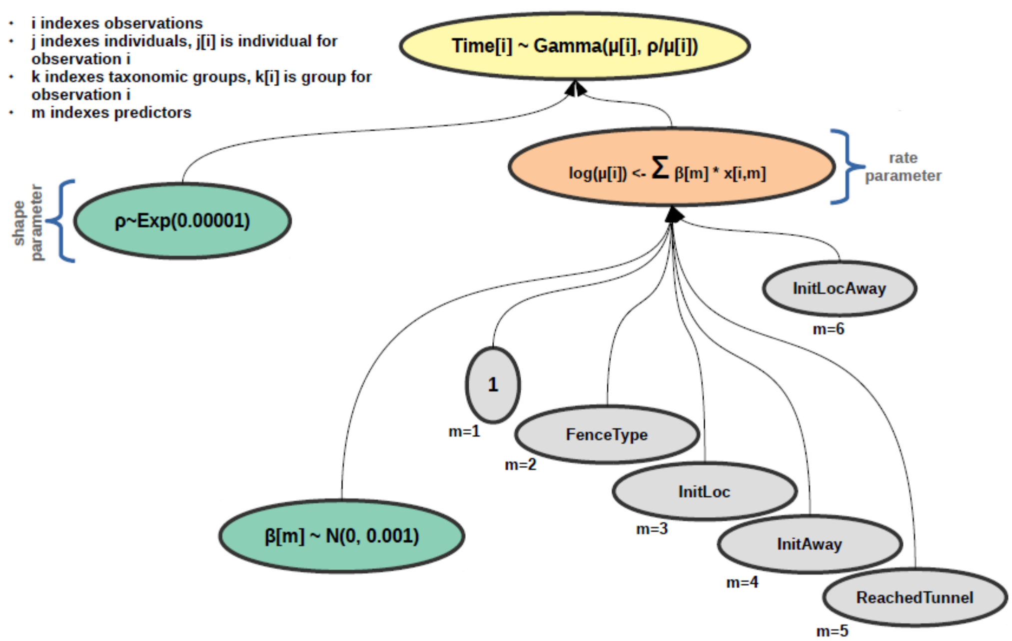

Figure 5. Gamma Regression for Distance Moved Along Fence

Tunnel System Permeability was calculated as the number of complete passes (individual detected at entrance and exit) divided by number of attempts. Other data, such as speed and turnaround rates, were also calculated.

Results

We documented 41 adult CTS over 4 nights in 2018 and 50 adults over 18 nights in 2019 moving along the fence-line. We did not compare individuals between years, and therefore, considered individual movements from 2018 and 2019 as independent in the analysis. Total precipitation during the winter months from November to March was 3.7 in. and 27.0 in. for 2018 and 2019, respectively (World Weather Online; Palo Alto). The average winter rainfall is 13 in. (Western Regional Climate Center Stn 046646-4). The Stanford University Conservation Program observed no recruitment in 2018 but confirmed high recruitment of CTS in 2019 (A. Launer and E. Adelsheim, pers. comm.).

Of the 91 CTS movements, 37 were along the solid fence line and 54 were along the mesh fence line. Fifty-six percent of CTS moved an estimated 25 m or less. Mean fence movement distances averaged approximately 40 m and did not differ by fence type. However, CTS movement speed was 43% slower and CTS changed direction an average of three times more frequently along the mesh fence than the solid fence (Table 1, Figure 6). Upon reaching the fence, 64% of CTS initially turned and moved in the direction of the passage system while 36% initially moved away from the passages. Two out of the three CTS that reached the fence ends 150 m from the passage system turned around and were subsequently documented on another camera 25-125 m away continuing to move back along the fence line.

Table 1. CTS Movement Metrics by Fence Type

		Fence Distance (m)		**Movement Speed (m/min)***		**Direction Changes (turnarounds/25m)**	
Fence Type	Sample Size	Mean	90% CI	Mean	90% CI	Mean	90% CI
Solid	37 (14*)	41.8	32.0- 47.8	2.1	1.7-2.5	0.13	0.04- 0.23
Mesh	54 (26*)	39.3	34.5- 42.2	1.2	1.0-1.4	0.41	0.15- 0.67

*individuals that passed more than one camera where movement speed was calculated

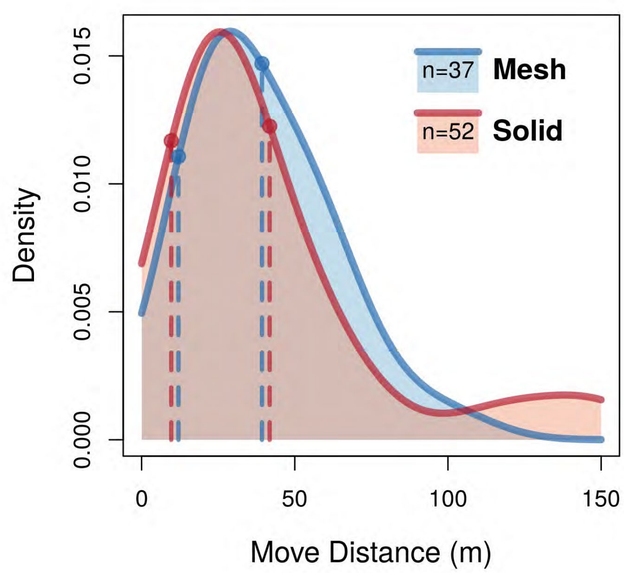

Figure 6. Distributions of Movement Distances by Fence Type. Lines Represent the Mean and Lower 90% Confidence Level Based on Cumulative Density of Observed Data.

The linear regression modeling indicates CTS moved longer distances if they encountered the fence farther away from the tunnel system. However, this was only if their initial direction choice was toward the tunnel system (Figure 7). There was no difference in predicted move distances for those CTS that encountered the fence and initially turned in the "wrong" direction

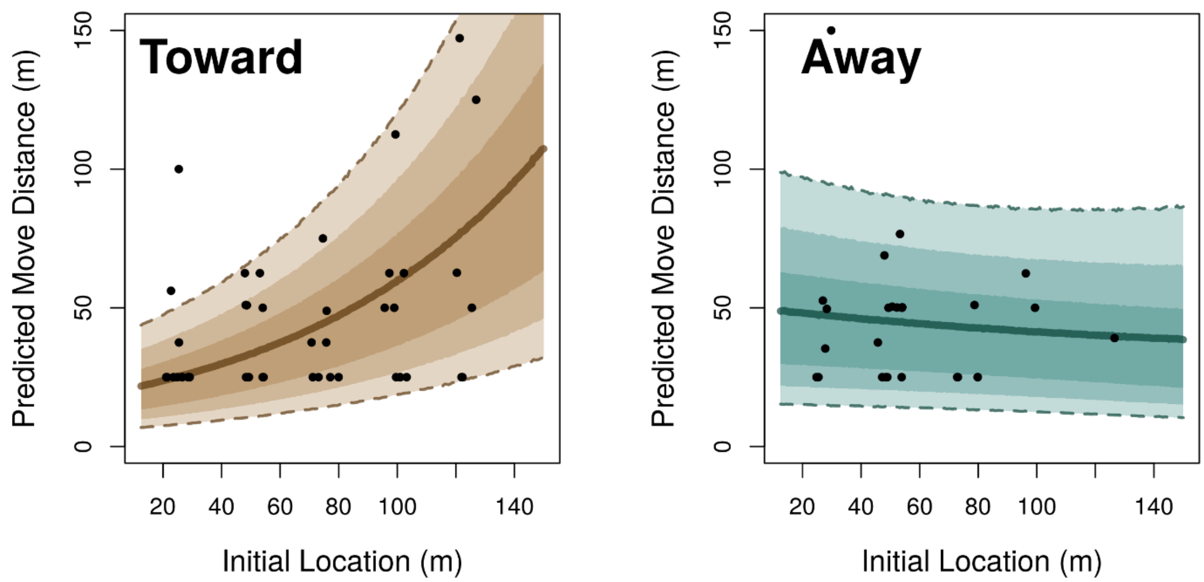

Figure 7. Movement Distance by Initial Location and Direction of Travel (Toward or Away from Underpass) with 90% Confidence Intervals.

The probability that CTS reached the tunnel system (0 m camera) decreased rapidly with increasing distance from the tunnels and was also highly dependent upon their initial direction choice. The average predicted probability of an individual reaching the tunnel system if the CTS encountered the fence at a distance of 25 m and was moving toward the tunnels was 0.48. This was reduced to only 0.15 if the CTS was initially moving away from the tunnels. Model estimated probabilities of success were lower along the mesh fencing than solid fencing, but fence type was not a significant predictor of success at reaching the underpass system (Table 2, Figure 8).

Table 2. Predicted Probabilities of Reaching Underpass by Initial Location and Direction of Travel (Toward or Away from Underpass)

	Solid Fencing				Mesh Fencing			
	TOWARD Underpass		AWAY from Underpass		TOWARD Underpass		AWAY from Underpass	
Initial Distance	Probability of Success	90% CI	Probability of Success	90% CI	Probability of Success	90% CI	Probability of Success	90% CI
12.5	.76	.57- .91	.35	.11- .64	.60	.37- .81	.20	.05- .42
25	.59	.38- .79	.21	.04- .46	.40	.21- .61	.11	.02- .24
50	.24	.08- .44	.07	.00- .25	.13	.04- .26	.03	.00- .10
75	.07	.01- .19	.03	.00-.15	.03	.00- .09	.01	.00- .06
100	.02	.00- .07	.02	.00-.10	.01	.00- .03	.01	.00- .04
125	.01	.00- .03	.01	.00- .06	.00	.00- .01	.00	.00- .02

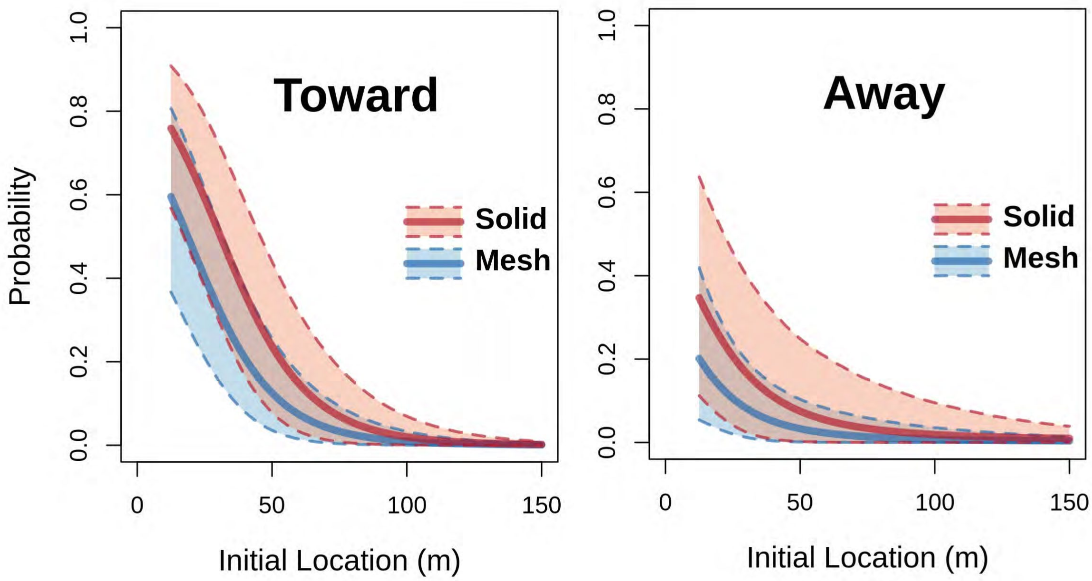

Figure 8. Probability of Reaching Underpass by Initial Location and Direction of Travel (Toward or Away from Underpass) with 90% Confidence Intervals.

Based upon timing, speed, and diagonal views of CTS entering and exiting the tunnels, we estimate that 5 to 11 out of the 51 CTS we documented traveling along the upland fence lines passed through the tunnel system from upland habitat toward the lake and 11 to 16 CTS entered the tunnels in the 20 m wide passage system without ever interacting with the fence. Once CTS entered a tunnel, there was a very high probability of them making it to the other side (0.89). Speed of passage through the tunnels was consistent with the speed at which CTS moved along the solid fencing (Table 3).

Table 3. Underpass System Permeability Metrics (2019)

No. CTS entered	No. CTS turned around	No. CTS successful passage	Tunnel System Permeability	Average Individual Passage Time (min:sec)		Average Passage speed (m/min)	
				Mean	90% CI	Mean	90% CI
41[a]	4	33[b]	0.89	6:33[c]	4:48- 8:18[c]	2.1[c]	1.5- 2.8[c]

[a] 4 CTS unknown if complete passage due to camera battery failure

[b] 22 CTS passed from upland to lake, 10 CTS passed from lake to upland, 1 CTS passed 3x from lake to upland to lake to upland

[c] a single passage time of 11 hours 18 min was excluded. Only CTS individual that spent day in passage.

Discussion

Our results showed that a relatively small proportion of the CTS that were documented migrating from upland habitat reached the passage system leading to breeding habitat at Lagunita Lake. CTS moved an average distance of 40 m along barrier fencing before "giving up" and their probability of making it to the passage system decreased rapidly with increasing distance from the tunnels.

The average distance moved by an individual CTS was 40 m. Approximately half of the individuals moved longer distances and half moved shorter distances before "giving up." This did not mean that all individuals moved along the barrier fencing in one direction and then either made it to the tunnel or gave up. Many individuals moved back and forth along the fencing and the 40 m represents the average span of total fence distance moved. Although this was an average, we estimated a fence span distance of less than 12.5 m would encompass 90% of population movements from the movement density distribution. Because our cameras were set 25 m apart, we were unable to estimate the specific distance with high confidence. Our logistic model predicted that 66% of individuals encountering the fence at the median distance of 12.5 m would successfully reach the tunnel system if headed toward the passage. For suggesting minimum distances between passages across a migratory pathway, we assume that either direction a CTS turns, it will encounter a passage. Therefore, these results suggest that underpasses spaced less than 12.5 m from one another along CTS migratory pathways could provide a high level of connectivity to the population. Future studies with cameras placed closer together will allow for more precise estimates for targeted levels of permeability.

In addition to distance moved, the direction the salamanders turned when reaching the barrier fencing was a large factor in whether they reached the passage system. CTS that reached the barrier fencing and then travelled in the wrong direction (away from the passages) were significantly less likely to reach the crossing than CTS that made the correct initial direction choice. In fact, CTS that made the correct initial direction choice were also more likely to travel longer distances to reach the passages.

Other studies have estimated average movement distances of migrating long-toed salamanders along fencing to be 27 m or less (Allaback and Laabs 2003, Pagnucco et al. 2012). These results are consistent with our findings and it would be expected that CTS move farther based upon their larger body size and longer migration distances. It is possible that not all CTS were making migratory movements during our study, as they may have been foraging. However, in that case we would expect to document the same individuals on multiple dates along the fence line which was rare in our study (2 out of 91 individuals). This was the first study to passively monitor individual movements of amphibians along fencelines and tunnels using new active trigger camera traps (HALT; Hobbs and Brehme 2017).

Previous studies have employed capture-recapture by hand and with pitfall traps to actively track individuals (Allaback and Laabs 2003, Pagnucco et al. 2012, Ottburg and van der Ree 2019, Matos et al. 2019). These active methods can potentially alter animal behavior, direction, speed, movement distances and require subsampling over the active period of the target species. Matos (2019) successfully used hand capture-recapture and fluorescent dye to track short distance foraging movements of newts (<26 m), however this method is not effective for monitoring movements over longer distances or time periods (e.g. Eggert 2002, Brehme et al. 2013). The use of these cameras coupled with individual identification by spot patterns allowed us to passively monitor species movements across the entire season along the fencing and underpasses unaffected by human presence. By calibrating cameras to atomic clocks, we were able to monitor not only distance but the precise speed of all individuals that passed by more than one camera.

It is also relevant to note that the barrier fencing was placed along a slightly curved road that created an approximate 10 to 20 degree angle leading to the passages and was perpendicular to the assumed main migratory path. Caltrans best management practices and others recommend installing barrier fencing at an angle into the habitat ("V" shaped toward the tunnel) in order to better lead migrating amphibians toward the tunnels (Federal Ministry of Transport 2000, Iuell et al. 2003, Schmidt and Zumbach 2008, Clevenger and Huijser 2011, Gunson et al. 2016, Langton and Clevenger 2021). There have not been any published studies we are aware of that directly compare the success of these configurations. However, the use of more directional fencing at a greater angle is expected reduce the proportion of individuals moving in the wrong direction away from the passage entrance. This configuration would also be expected increase movement distances along fencing because it is closer to the trajectory of the migrating amphibians. For these reasons, it is estimated that distances between passages can be farther apart with more directional fencing than with perpendicular fencing to accomplish the same level of permeability (e.g. Langton and Clevenger 2021). However, these "V" shaped configurations typically require planning of multiple passages that are spaced apart across an entire migratory pathway. In this case, there is a single crossing structure of 3 passages and placing fencing at greater angles would have excluded a substantial amount of upland CTS habitat.

If fencing must be set parallel to the roadway along an easement, it is possible that small turnarounds placed at frequent intervals along the fencing would be effective in turning individuals moving away from the tunnels in the right direction closer to the tunnel system (rather than only at fence ends). Turnarounds were shown to be effective for two out of three individuals that reached the fence ends in our study and have been shown to be effective at changing the initial trajectory of movement for lizards, snakes and toads in San Diego (Chapter 7). Future studies on the effects of multiple turnarounds are planned for this and other study sites.

The transparency of fencing (mesh vs. solid) did not significantly affect the movement distances or probability of CTS making it to the underpass system. However, the speed and time of travel were significant by fence type. CTS moving along solid fencing moved at almost twice the average speed and were 3 times less likely to turn around and repeatedly move back and forth. This indicates that CTS moving along fencing that they can see through results in them expending a higher amount of energy to make it to the crossing. We and others have shown in other studies (Ruby et al. 1994, Milburn-Rodríguez et al. 2016, Chapter 6) that animals interact with transparent fencing with behaviors such as poking, attempting to climb, and moving back and forth. Higher energy and time expenditures of these behaviors may have negative impacts on breeding success (Carr 2011, Navas et al. 2016). However, mesh fencing has benefits in ease of installation, increased permeability to wind and water, and reduced temperature and wind differentials from the surrounding environment (Boyle et al. 2019, Langton and Clevenger 2021). In concurrent studies on lizards, snakes and toads (Chapter 6), we have found that addition of a visual barrier along the bottom edge of the fence is effective in both reducing these fence interaction behaviors and increasing the speed of movement to that comparable to a full solid barrier. The potential use of visual barriers should allow flexibility in choosing fence materials for amphibian crossing systems. We intend to test this as part of a Before-After Control-Impact study at the Stanford CTS site.

Therefore, the likelihood by distance that animals reach a passage can inform the planning and spacing of crossing systems for migratory amphibians and other migratory species. Without considering this, it is possible that barrier effects of the mitigation could be worse to survivorship and connectivity than the original road mortality problem (Jaeger and Fahrig 2004, Ottburg and van der Grift 2017). This applies when high connectivity is important for the persistence of the population, such as with migratory amphibian species that must make population level movements between upland and breeding habitats (Semlitsch 2008, Hamer and McDonnell 2008, Hamer et al. 2015).

Finally, CTS that did reach the opening of the underpass system at Stanford University had a very high probability (89%) of making a complete crossing to the other side. The tunnels in our study were specially built for amphibians in that they are made of inert materials and incorporate a grid ceiling to allow natural light, moisture and rainfall to permeate the length of the passage. These have been shown to be highly permeable to amphibian movement in other locations, particularly throughout Europe (see review by Langton and Clevenger 2017). Maintenance of barrier fencing and tunnel systems is important for long term success. This includes regular inspection and repair of fencing, maintenance of vegetation by the fencing to prevent climbing, and clearing of excess debris from the tunnels (e.g. Schmidt and Zumbach 2008, van der Ree et al. 2015, Langton and Clevenger 2021).

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References

Allaback, ML. and DM Laabs. 2002. Effectiveness of road tunnels for the Santa Cruz long-toed salamander. Transactions of the Western Section of the Wildlife Society 38: 5–8.

Bolster BC. 2010. A status review of the California tiger salamander (*Ambystoma californiense*). Report to the Fish and Game Commission, State of California. Nongame Wildlife Program Report 2010–4.

Boyle, SP, R Dillon, JD Litzgus and D Lesbarrères. 2019. Desiccation of herpetofauna on roadway exclusion fencing. The Canadian Field-Naturalist 133(1): 43–48.

Brehme, CS, JA Tracey, LR McClenaghan and RN Fisher, 2013. Permeability of roads to movement of scrubland lizards and small mammals. Conservation Biology, 27(4), pp.710-720.

Brehme CS, SA Hathaway, and RN Fisher. 2018. An objective road risk assessment method for multiple species: Ranking 166 reptiles and amphibians in California. Landscape Ecology 33(6): 911–935.

Carr, JA. 2011. Stress and reproduction in amphibians. In Hormones and Reproduction of Vertebrates. Academic Press, pp. 99–116.

City of Menlo Park. 2017. Traffic Volume Data. *https://www.menlopark.org/1543/Traffic-volume-data*. Accessed May 13, 2020.

Clevenger, AP and MP Huijser. 2011. Wildlife crossing structure handbook: design and evaluation in North America (No. FHWA-CFL-TD-11-003). United States. Federal Highway Administration. Central Federal Lands Highway Division.

Congdon, P. 2006. Bayesian Statistical Modeling. 2nd ed. Wiley, West Sussex, England. 573 pages, see pp. 221–224.

Denwood, MJ. 2016. Runjags: An R package providing interface utilities, model templates, parallel computing methods and additional distributions for MCMC models in JAGS. Journal of Statistical Software 71(9): 1–25.

Eggert, C. 2002. Use of fluorescent pigments and implantable transmitters to track a fossorial toad (*Pelobates fuscus*). Herpetological Journal, 12(2): 69-74.

Eigenbrod F, SJ Hecnar and L Fahrig. 2008. The relative effects of road traffic and forest cover on anuran populations. Biological Conservation 141(1): 35–46.

Federal Ministry of Transport (Germany), Building and Housing, Road Engineering and Road Traffic. 2000. Merkblatt zum Amphibienschutz an Straßen 28 p. Germany [Guidelines for amphibian protection on roads, In German]

Gibbs JP. 1998. Amphibian movements in response to forest edges, roads, and streambeds in southern New England. Journal of Wildlife Management 62: 584–589.

Gunson, K, D Seburn, J Kintsch and J Crowley. 2016. Best Management Practices for Mitigating the Effects of Roads on Amphibian and Reptile Species at Risk in Ontario. Ontario Ministry of Natural Resources and Forestry. Queen's Printer for Ontario. 112 pp.

Hamer, AJ and MJ McDonnell. 2008. Amphibian ecology and conservation in the urbanising world: a review. Biological Conservation, 141(10): pp. 2432–2449.

Hamer, AJ, TE Langton and D. Lesbarrères. 2015. Making a safe leap forward: mitigating road impacts on amphibians. Handbook of Road Ecology, pp. 261–270.

Helldin JO and SO Petrovan. 2019. Effectiveness of small road tunnels and fences in reducing amphibian roadkill and barrier effects at retrofitted roads in Sweden. PeerJ 7:e7518 *https://doi.org/10.7717/peerj.7518*.

Hobbs, MT and CS Brehme. 2017. An improved camera trap for amphibians, reptiles, small mammals, and large invertebrates. PLOS ONE, 12(10), p.e0185026.

Iuell, B, GJ Bekker, R Cuperus, J Dufek, G Fry, C Hicks, V Hlaváč, V Keller, B Rosell, T Sangwine and N Třrslřv. 2003. COST 341–Wildlife and traffic: a European handbook for identifying conflicts and designing solutions. URL: *https://www. milieuinfo. be/productie/beheerplone/nietacm/iene/cost-341/COST*.

Jaeger, JA and L Fahrig. 2004. Effects of road fencing on population persistence. Conservation Biology 18(6): 1651–1657.

Jochimsen DM, CR Peterson, KM Andrews, and J Whitfield Gibbons. 2004. A literature review of the effects of roads on amphibians and reptiles and the measures used to minimize those effects. Idaho Fish and Game Department and USDA Forest Service Report.

Langton, TE. 1989. Amphibians and roads; proceedings of the Toad Tunnel Conference, Rendsburg, Federal Republic of Germany, 7-8 January 1989. In Toad Tunnel Conference, 1989, Rendsburg, West Germany.

Langton, TES and AP Clevenger. 2017. Amphibian and Reptile Highway Crossings: State of the practice, gap analysis and decision support tool. Report prepared for the State of California, Department of Transportation, Division of Research, Innovation and System Information., Office of Materials and Infrastructure Research, June 2017.

Langton, TES and AP Clevenger. 2021. Measures to Reduce Road Impacts on Amphibians and Reptiles in California. Best Management Practices and Technical Guidance. Prepared by Western Transportation Institute for California Department of Transportation, Division of Research, Innovation and System Information.

Matos, C, SO Petrovan, PM Wheeler, and AI Ward. 2019. Short-term movements and behaviour govern the use of road mitigation measures by a protected amphibian. Animal Conservation 22(3): 285–296.

Milburn-Rodríguez JC, J Hathaway, K Gunson, D Moffat, S Béga and D Swensson. 2016. Road mortality mitigation: The effectiveness of Animex fencing versus mesh fencing. *https://animexfencing.com/whyanimex/animex-vs-mesh.*

Navas, CA, FR Gomes and EA De Domenico. 2016. Physiological ecology and conservation of anuran amphibians. Amphibian and Reptile Adaptations to the Environment: Interplay Between Physiology and Behavior. DV de Andrade, CR Bevier, and JE de Carvalho (eds.). CRC Press, Boca Raton, Florida, pp. 155–188.

Orłowski G. 2007. Spatial distribution and seasonal pattern in road mortality of the common toad *Bufo bufo* in an agricultural landscape of south-western Poland. Amphibia-Reptilia 28(1): 25–31.

Ottburg, FG and EA van der Grift. 2019. Effectiveness of road mitigation for common toads (*Bufo bufo*) in the Netherlands. Frontiers in Ecology and Evolution 7: 23.

Hamer, A.J. and McDonnell, M.J., 2008. Amphibian ecology and conservation in the urbanising world: a review. Biological Conservation, 141(10): 2432–2449.

Pagnucco KS, CA Paszkowski and GJ Scrimgeour. 2012. Characterizing movement patterns and spatio-temporal use of under-road tunnels by long-toed salamanders in Waterton Lakes National Park, Canada. Copeia 2012(2): 331–340. DOI 10.1643/CE-10-128.

Rasband, WS. ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, *https://imagej.nih.gov/ij/,* 1997–2018.

Ruby, DE, JR Spotila, SK Martin, and SJ Kemp. 1994. Behavioral responses to barriers by desert tortoises: implications for wildlife management. Herpetological Monographs 8: 144–160.

Semlitsch, RD. 1998. Biological delineation of terrestrial buffer zones for pond-breeding salamanders. Conservation biology, 12(5), pp. 1113-1119.

Schmidt, BR and S Zumbach. 2008. Amphibian Road Mortality and How to Prevent It: A Review. In: Mitchell, JC; RE Jung Brown, and B Bartolomew. Urban Herpetology. St. Louis, Missouri, 157-167.Semlitsch, RD. 2008. Differentiating migration and dispersal processes for pond-breeding amphibians. Journal of Wildlife Management, 72(1): 260–267.

Trenham PC. 1998. Demography, migration, and metapopulation structure of pond-breeding salamanders. Ph.D. dissertation. University of California, Davis.

Trenham PC, WD Koenig, and HB Shaffer. 2001. Spatially autocorrelated demography and interpond dispersal in the salamander *Ambystoma californiense*. Ecology 82(12): 3519–3530.

Trenham PC, WD Koenig, MJ Mossman, SL Stark and LA Jagger. 2003. Regional dynamics of wetland-breeding frogs and toads: turnover and synchrony. Ecological Applications 13(6): 1522–1532.

Van Tienhoven AM, JE Den Hartog, RA Reijns, and VM Peddemors. 2007. A computer-aided program for pattern-matching of natural marks on the spotted raggedtooth shark *Carcharias taurus*. Journal of Applied Ecology 44: 273–280. *https://reijns.com/i3s/.*

van der Ree, R, JW Gagnon and DJ Smith. 2015. Fencing: a valuable tool for reducing wildlife-vehicle collisions and funneling fauna to crossing structures. Handbook of Road Ecology. Oxford: John Wiley & Sons, pp. 159–171.

Chapter 5. Movement of Yosemite Toads Along Barrier Fencing and a Novel Elevated Road Segment in Sierra National Forest, CA

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Introduction

Amphibians have been identified as being particularly susceptible to the negative effects of roads within their habitat (e.g. Forman et al. 2003, Rytwinski and Fahrig 2012, Andrews et al. 2015a, 2015b). Many are slow moving, do not avoid roads, and are simply too small for drivers to avoid. During rains many amphibians make long linear terrestrial movements regardless of the presence of intersecting roadways (Glista et al. 2008). In particular, pond breeding amphibians use both aquatic and terrestrial habitat for breeding, development, foraging, and overwintering, and therefore, require connectivity within and between aquatic and terrestrial habitats to support basic life history requirements. Increased mortality of amphibian populations from vehicles using roads that intersect breeding and upland habitat, if significant, can result in reduced population sizes and increased probability of extirpation (e.g. Hamer et al. 2008, Semlitsch 2008, Brehme et al. 2018, Ottburg and van der Grift 2019).

Bufonid toads can move large distances (>1 km) in both aquatic and terrestrial habitats to satisfy their annual resource requirements, and there is evidence that bufonid toads are particularly susceptible to negative impacts from roads (Trenham et al. 2003, Orłowski 2007, Eigenbrod et al. 2008). Endangered and threatened species are considered at risk of extirpation, often due to multiple stressors, and are thus thought to be less likely to be resilient to additional road impacts. Because of these attributes, the Yosemite toad ranked in the highest risk category for susceptibility to negative road impacts in a recent road risk assessment of 166 species of reptiles and amphibians in California (Brehme et al. 2018).

The Yosemite toad is a relatively long-lived toad (12–15 years) that inhabits high elevation, open, montane meadows, willow thickets, and adjoining forests in the Sierra Nevada, California. This species breeds in shallow edges of snowmelt pools and ponds or along edges of lakes and slow-moving streams. Some breeding sites dry up before larvae metamorphose. Females may breed every other year or once every three years. Although still distributed over most of its original range with many populations actively breeding and recruiting (Shaffer et al. 2000), the species has declined or disappeared from more than 50% of the sites from which it has been recorded (Jennings and Hayes 1994, Drost and Fellers 1996, USFWS 2014). Hypotheses for declines include habitat loss and degradation, disease (chytridiomycosis), airborne contaminants, livestock grazing, drought, fish predation, raven predation, road mortality and vehicle vibration effects (e.g. Hammerson et al. 2004, Davidson and Fellers 2005, USFWS 2014).

In 2017, the U.S. Forest Service, Sierra National Forest reported 126 Yosemite toads that had been run over and killed by vehicles on Forest Service roads. Of these, 92 subadults were found on the 9S09 road between June 24 and October 24. The Forest Service and U.S. Fish and

Wildlife Service are particularly concerned about the potential for increased Yosemite toad road mortality due to increased vehicular traffic projected for these roads in the future.

Elevated Road Segment

A common road mitigation strategy for amphibians is to install small passages under the roadway in combination with attached barriers or fencing (1 to 2 feet or more high). The barriers are used to prevent animals from going out onto the roadway and to funnel them toward the passage(s). However, there is evidence that inadequate underpass spacing between uplands and breeding ponds may result in population declines in pond breeding amphibians (Ottburg and van der Grift 2019).

The life history of the Yosemite toad presented a unique challenge to this common mitigation strategy. Yosemite toad adults move from upland habitats to wetlands to breed during early snow melt in the spring, and then migrate back into the upland habitats shortly after breeding. Therefore, a passage-barrier system would likely only be effective for reducing road mortality during post breeding toad migrations to uplands after most of the snow has melted or during the summer migrations (including juveniles). Secondly, Yosemite toads have been shown to travel in straight line trajectories over wide areas, resulting in long lengths of roadways where they are susceptible to road mortality without any clearly defined "hot spots".

Finally, the road is on a flat landscape, with an upland slope on one side and downward slope on the other. Burrowing passage(s) under the road would require a significant amount of grading and re-contouring on the upland slope side to make passage entrances accessible.

To meet these challenges, in June of 2018, we designed and installed a new road crossing structure in a high road mortality section of 9S09 (Figure 1). The crossing structure is an elevated roadway segment placed on top of the existing road surface and composed of hardwood laminated billet road mats that are designed for use by heavy equipment at construction sites (Emtek®). The road mats are approximately 6 in. thick and were installed on top of 8-in. high support bars installed on and perpendicular to the road, allowing for passage of small animals. They were built to meet codes and specifications for U.S. Forest Service, County, and City roads.

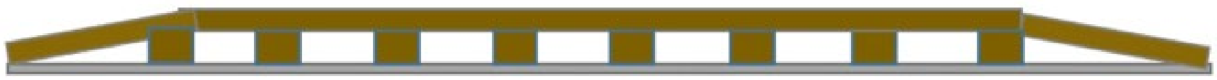

Diagram: Side view depiction of elevated road segment (rectangle with vertical lines) with barrier fencing (lines) and openings for toad passage underneath (solid rectangles); not to scale.

Figure 1. Diagram and Photos of Elevated Road Segment.

This proposed study is part of a larger USGS research program in collaboration with the Western Transportation Institute (WTI; Montana State University) for the California Department of Transportation (Caltrans). The larger study provides research to inform best management practices for barrier and crossing systems for sensitive amphibians and reptiles in California.

Movement along Barrier Fencing

The common toad, *Bufo bufo*, in the Netherlands turned around after an average of 50 m if they did not reach an underpass (Ottburg and van der Grift 2019). As with the California tiger salamander (Chapter 4), the distance Yosemite toads may travel along a barrier fence to find a passable crossing is unknown. Therefore, a study was warranted to determine toad movement distances along barriers to inform proper passage spacing for the Yosemite toad. There is also evidence that animals may spend more time trying to climb or get through opaque fencing compared to solid fencing (Milburn-Rodríguez et al. 2016). Therefore, we were also interested in whether fencing opacity affects the probability or speed at which the toads and other amphibians find wildlife crossings.

The results of this study will help to gauge effectiveness of this new road crossing structure, identify underpass spacing needs, evaluate barrier materials, and assess the effectiveness of fence end turnarounds for pond breeding amphibians.

Research questions:

1) What is the probability a Yosemite toad will reach an underpass based upon the distance from the underpass an animal first encounters the barrier wall?
2) How quickly do toads travel along the barrier wall toward the crossing structure?
3) How does the opacity of fencing effect the questions above?
    a. Solid barrier (high-density polyethylene (HDPE-2); Animex®)
    b. Semi-transparent barrier (water- permeable rigid polymer matrix; ERTEC® E-Fence, referred to hereon as "mesh")
5) Is the elevated roadway segment effective in reducing road mortality while maintaining connectivity between breeding wetlands and uplands for the Yosemite toad?

Study Location:

U.S. Forest Service Road 9S09 in Sierra National Forest, CA between Yosemite toad breeding and upland habitat.

Methods

Field Study

We studied the movement of Yosemite toads adjacent to and under the ERS structure along 9S09 in Sierra National Forest, CA in the breeding seasons of 2018 and 2019. The road bisects a Yosemite toad breeding meadow and upland habitat (Figure 2).

B) B)

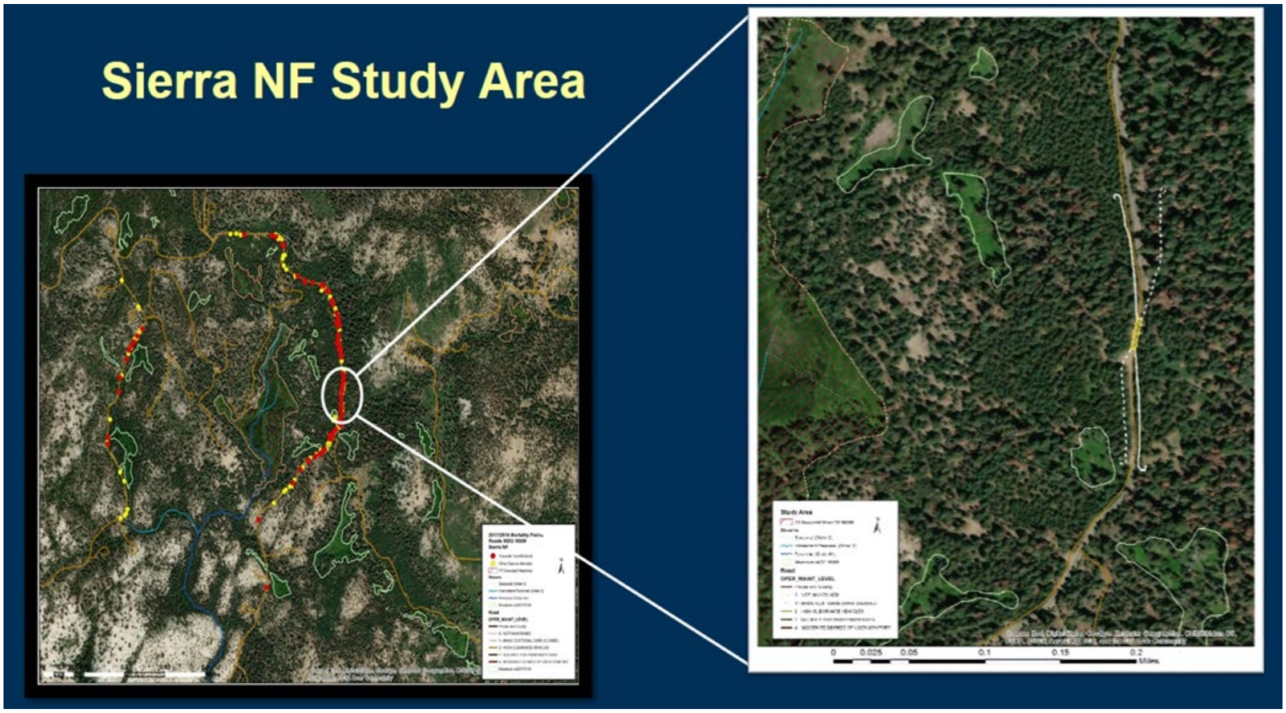

Figure 2. Maps of A) Yosemite Toad Road Mortality and B) Location of Barrier and Elevated Road Crossing in Sierra National Forest Between Upland and Breeding Habitat.

A total of approximately 480 m of barrier fencing was installed along the east and west sides of 9S09 (~120 m in each direction) connected to the ERS crossing. One portion of the fencing installed was semi-transparent (ERTEC ® rigid polymer matrix E-Fence^{TM}) and the other portion was solid (Animex® high-density polyethylene (HDPE-2)). Jump-outs (ERTEC® cones and high berms) were installed a minimum of every 10 m along the fence to provide toads and other small vertebrates a way to get back into the habitat if they ended up on the road side of the barrier fencing. At outer fence ends, turnarounds were installed to redirect animals away from the road and back toward the upland habitat in a U-shaped fashion. The turnarounds were approximately 2 m long and 1 m in width. Fencing was installed with the bottom buried in the ground according to manufacturers' guidelines.

HALT ® camera systems (Hobbs and Brehme 2017) were placed against the fencing every 20 m along the new fence lines from 0 to 100 m from the ERS (Figures 3 and 4). Each 0 m camera was approximately 8 m from the closest ERS opening to allow them to be shielded from the view of forest visitors. Cameras were set up on the wetland side as soon as possible after the road opened (spring) and were checked weekly to collect data on toads during their upland migration.

Figure 3. Schematic of Elevated Road Segment, Mesh Fencing (Dotted Lines), Solid Fencing (Lines), HALT Cameras (Circles), and Time Lapse Cameras (Black Circles); Not to Scale.

At fence end turnarounds, HALT camera systems were placed above the end terminal to record video of animals' movement trajectory after reaching the fence-ends (2018). Due to evidence of CTS turning around but not being recorded on video, in 2019, we narrowed the end of the turnaround so that the edge of the "U" was 0.4 m from the beginning of the turnaround creating a tear drop shape. This allowed us to install the trigger at the turnaround opening so that we could record animals entering and exiting the turnaround.

The extreme width of the ERS underpass made it impossible to sample completely; therefore, we had to subsample underpass activity in both space and time. For this, we placed HALT camera systems under both ERS intersections with the fence line on the west side to record tunnel entrances. We then set eight Reconyx cameras set to a time lapse of every 5 minutes on the upland side under the ERS to gather more data on animal movements.

All cameras were set as soon as the snow melted and road opened, and then checked on a weekly basis during the late spring and summer (May–Oct. 2018 and July–Oct 2019). Each time we set and checked the cameras, we took a photo of a battery powered atomic clock in order to calibrate exact minutes and seconds upon processing.

Road mortality surveys were conducted along 9S09 by the U.S. Forest Service.

Figure 4. Solid (A) and Mesh (B) Fence Lines. Along the Fences are Jump Outs and Cameras within Plastic Bins Facing Down Toward HALT Triggers.

Analysis

Movement along fence line

Photos of all Yosemite Toads were analyzed using pattern recognition software to identify individuals by their unique spot patterns (I^{3}S Spot; Van Tienhoven et al. 2007; Figure 5). Camera location, time, and direction of movement were recorded for each individual. Snout to vent length was measured with Program ImageJ (Rasband 1997-2018) using the 1 cm grids from the HALT trigger for calibration.

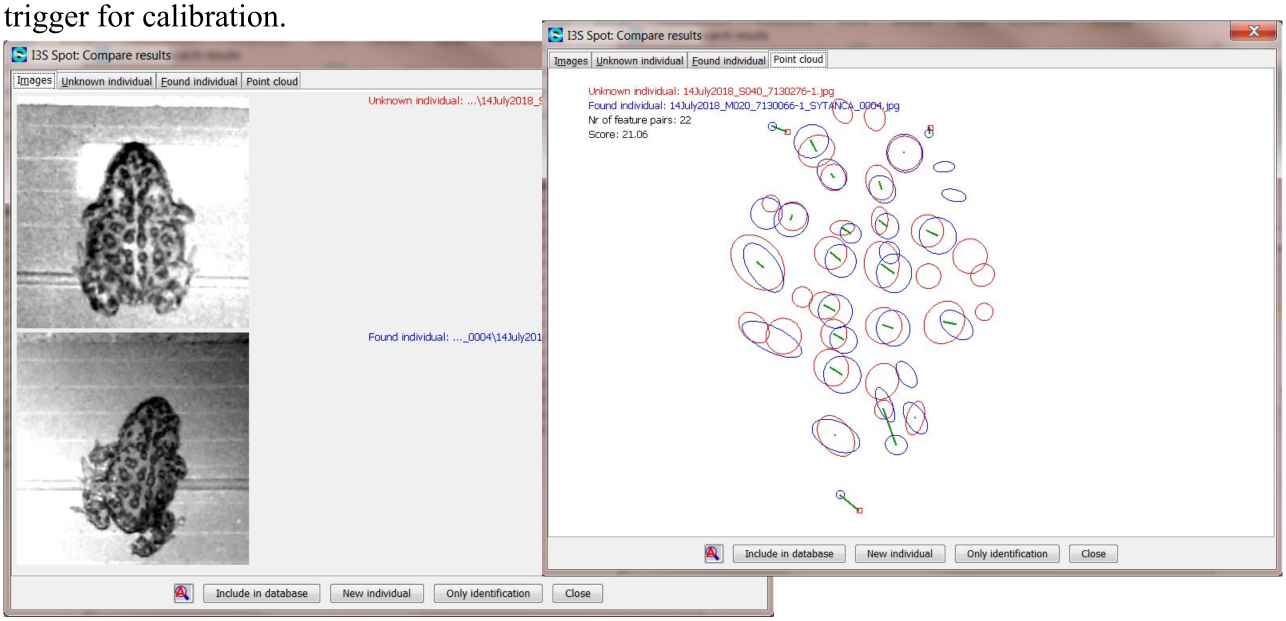

Figure 5. Example of Yosemite Toad Identified to Individual Using i3s Software to Distinguish Spot Patterns.

For individual Yosemite Toads, we then calculated movement distances along the fence lines, numbers of turn arounds, speed, and "success" at reaching 0 m cameras next to underpass system. Because cameras were placed 20 m apart, our margin of error for estimating fence movement distance ranged between 0 and 20 m. For instance, if an animal was only detected at a single camera, then our average estimated distance was 20 m (10 m before reaching the camera and 10 m after exiting the camera). Similarly, if an individual was detected at multiple consecutive cameras moving in the same direction, our margin of error was typically 20 m. In the instances where individuals were detected at consecutive cameras, we also calculated the movement speed between segments. If such an individual then turned around and was re-detected at a camera while moving in the other direction, we estimated the distance travelled along the fence before turning around by multiplying the time between detections by its average speed. Because of this, if individuals travelled back and forth several times, we were able to more accurately estimate the total distance of fence line traversed (fence movement distance). If an individual reached the 0 m camera (where the experimental fence lines attached to the short length of existing fence), this was considered a "success" at reaching the passage system with no added error for distance moved afterward.

For models of movement along fence line, we used Markov Chain Monte Carlo (MCMC) implemented in the R programming language and the runjags package to interface with JAGS (Just Another Gibbs Sampler) to sample values of all unknown parameters from the joint posterior distribution. In each case, four chains were sampled to perform standard diagnostics for convergence. In all cases, non-informative prior distributions were used for all parameters.

Logistic Regression for Success in Reaching Underpass Opening

We modeled the probability of success of Yosemite toads in reaching the 0 m camera near the crossing opening. For this, we used a Bayesian approach to logistic regression modeling (Figure 6). The response was a Bernoulli random variable, where 0 indicates failure and 1 indicates success in being detected by the camera at the opening of the crossing (ReachedTunnel). The probability of success for the Bernoulli distribution is a logistic (i.e. $p = \exp(y)/(1 + \exp(y))$ function of the linear component of the model that consists of four predictors (FenceType, InitLoc, InitAway, InitLocAway) and five parameters that include an intercept and a regression coefficient corresponding to each of the predictors. FenceType is a binary variable where 0 indicates a mesh fence and 1 indicates a solid fence. InitLoc is the position along the fence where the animal was first detected in meters from the crossing opening (with error described in the previous paragraph), InitAway is a binary variable where 0 indicates that the animal was initially moving toward the crossing and 1 indicates it was initially moving away from the crossing, and InitLocAway is an interaction (product of) InitLoc and InitAway. All predictors were standardized (the mean subtracted from each value and then divided by the standard deviation) prior to modeling. The priors for the parameters were non-informative normal distributions with mean 0 and 0.001 precision (i.e. a variance of 1000). The parameters were sampled from their posterior distributions using MCMC (as described above) and described by mean, median, and quantiles of their marginal distributions. This allowed us to assess the effect of each predictor on the probability of success.

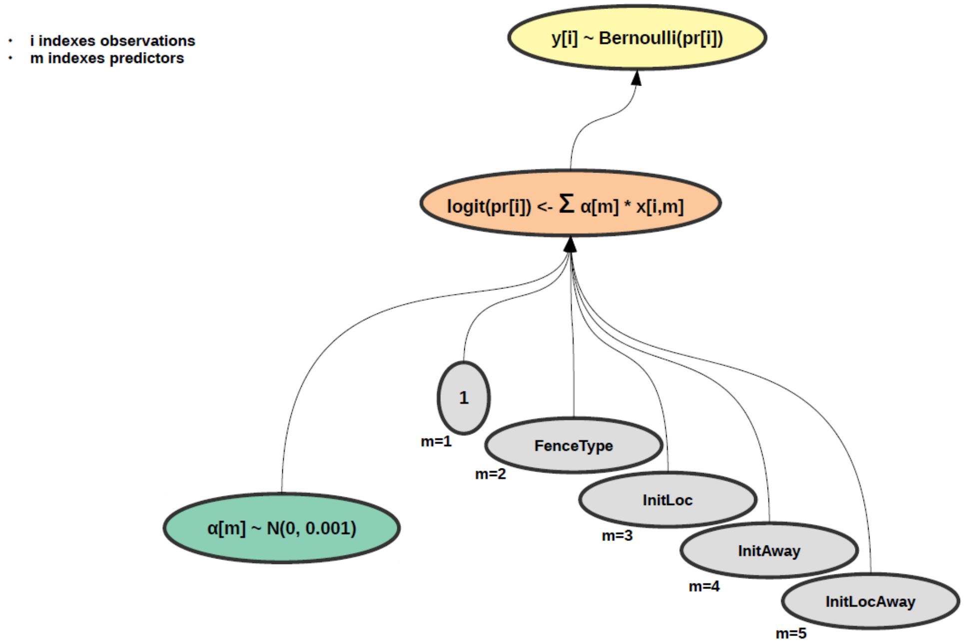

Figure 6. Logistic Regression for Success in Reaching Underpass Opening

Gamma Regression for Distance Moved Along Fence

We also modeled the distance that Yosemite toads moved along the fence. We used a Bayesian approach to regression modeling of the probability of successfully reaching the underpass opening (Figure 7). The response was assumed to be a gamma distributed random variable, which is a continuous positive variable representing the distance the animal moved along the fence as described. The gamma distribution has a shape parameter, which we assumed to be independent of any predictors, and a rate parameter that we model as an exponential (i.e. rate = exp(y)) function of the linear component of the model that consists of four predictors FenceType, InitLoc, InitAway, ReachedTunnel, InitLocAway and six parameters that include an intercept and a regression coefficient corresponding to each of the predictors. All predictors, except for ReachedTunnel, were standardized prior to modeling. The prior for the shape parameter was a non-informative exponential distribution with a rate of 0.00001. The priors for the regression parameters for the rate were normal distributions with mean 0 and 0.001 precision (i.e. a variance of 1000). The parameters were sampled from their posterior distributions using MCMC (as described above) and described by mean, median, and quantiles of their marginal distributions. This allowed us to assess the effect of each predictor on the distance moved along the fence.

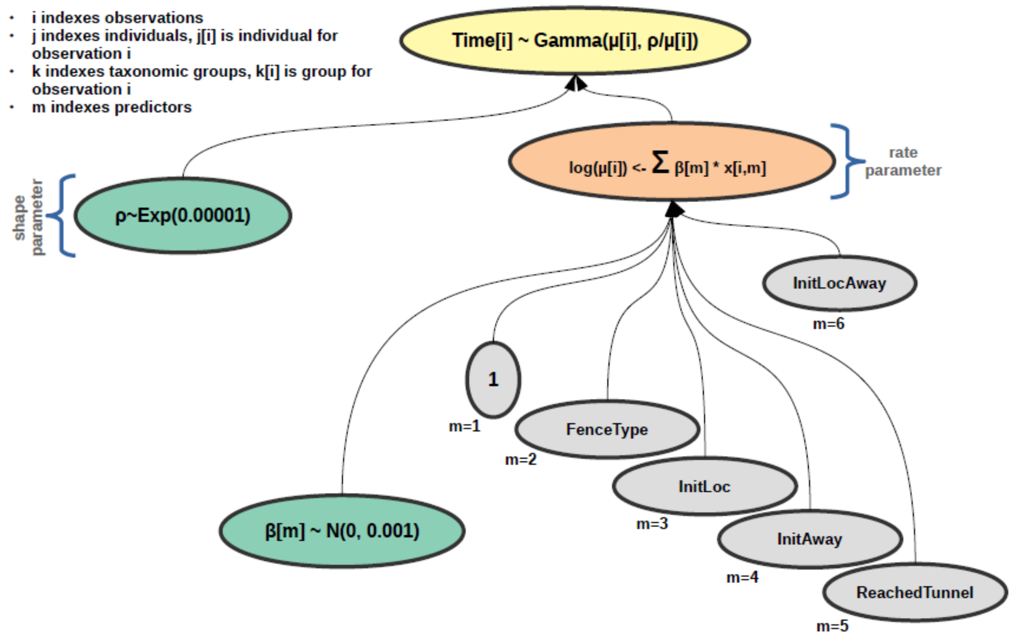

Figure 7. Gamma Regression for Distance Moved Along Fence

Elevated Road Segment Crossing

Because the ERS crossing system is so wide (>100 ft), it was not possible to monitor the entire underpass. Therefore, we subsampled by placing two HALT cameras along the fence lines underneath the ERS (wetland side) and eight Reconyx time lapse cameras underneath middle portions of the ERS on the upland side (Figure 1: not to scale). All active trigger camera images were considered a single species event if within one minute of each other. Because of the large number of time lapse images generated, they were only scanned for the presence of Yosemite toads during time periods they were detected with the HALT cameras along the fence lines.

To assess ERS crossing permeability, we analyzed the number of individual Yosemite toads monitored along the fence that reached the passage. For all species, we also compared the relative number of species detections immediately outside the ERS (red circles; 0 m cameras) vs. under the ERS on each side (yellow circles; Figure 8).

Red circles: HALT cameras immediately outside of ERS system
Yellow circles: HALT cameras underneath ERS adjacent to the fence line
Black open circles: Time lapse cameras placed underneath the ERS on the upland (terrestrial) side facing toward the wetland habitat side. Note: length of ERS not to scale and numbers of time lapse cameras greater than depicted (8).

Figure 8. Schematic of General Locations of Cameras Used to Monitor ERS Permeability (Red and Yellow Circles).

Results

Due to road closures during winter and spring months, we began monitoring upland toad movements immediately after snow melt and during the summer months when toads are typically active and moving during rainfall events. Total summer precipitation in nearby Huntington Lake during the monitoring periods was 1.12 in. for 2018 (June-Oct) and 0.59 in. for 2019 (July- Oct) after the snow melt (Huntington Lake Historical Weather; worldweatheronline). Both summer seasons were approximately 3.0 in. below average rainfall during these periods (Western Regional Climate Center 044176-5). Breeding and recruitment were documented by USFS in 2019; however, we likely missed most of the upland dispersal at the site due to the extended period of snowpack through June and lack of access to the site during this time.

Fence Movement

We documented a total of 37 individually identified Yosemite toads in 2018 (24 over 12 nights) and 2019 (13 over 6 nights) moving along the fence-line. Five or fewer individuals (5 photos) were not included in the initial analysis due to low confidence in these identifications. Of the 37 individuals in the analysis, 19 were subadults (<44 mm snout-to-vent length (SVL)) and 18 were adults (>44 mm SVL). Among fence types, eight subadults and 13 adults were recorded along the mesh and 11 subadults and five adults were recorded along the solid. We considered individual movements from 2018 to 2019 as independent in the analysis.

Because our sample size was low, confidence intervals are extremely wide for most parameters. We present averages and confidence intervals of fence distance, movement speed, and direction changes (i.e. back and forth movements) among fence types and age classes in Table 1.

Fence movement distances averaged approximately 52 m (Table 1, Figure 9) and did not significantly differ by fence type or age class, although mean distance moved was farther along the solid (63 m) than mesh (43 m) fencing. With these preliminary data, there were no significant differences in the response variables by fence type. Yosemite toads moved an average of 1 m/min and changed directions an average of 0.5 times per 20 m (i.e. per camera location). Adults were 71% faster than subadults and changed directions 75% more often, although not significantly.

Seven out of 10 Yosemite toads changed course at a turnaround back toward the fence line or out into habitat, and of these, four toads were subsequently documented on other cameras 40-80 m away continuing to move back along the fence line.

Table 1. Yosemite Toad Movement Metrics by Fence Type and Age Class

			Fence Distance Moved (m)		Movement Speed (m/s)*		Direction Changes per 20m	
		Sample Size	Mean	90% CI	Mean	90% CI	Mean	90% CI
By Fence Type	Solid	16 (13*)	63.3	10- 109	1.0	0.7- 1.3	0.6	0.3- 0.9
	Mesh	21 (9*)	43.2	10- 105	0.9	0.6- 1.2	0.5	0.2- 0.8
By Age Class	Subadult	19 (13*)	48.9	38.3- 59.6	0.7	0.6- 0.9	0.4	0.2- 0.6
	Adult	18 (9*)	43.1	30.0- 56.3	1.2	1.0- 1.5	0.7	0.4- 1.0
All Toads		**37**	**52.3**	**10- 110**	**1.0**	**0.6- 1.3**	**0.5**	**0.3- 0.7**

*individuals that passed more than one camera w here movement speed w as calculated

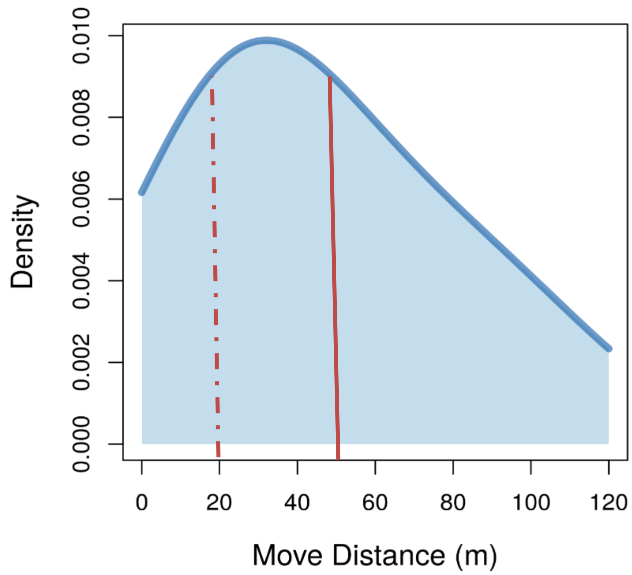

Figure 9. Distributions of Movement Distances. Lines Represent Mean (Solid) and Lower 90% Confidence Interval (Dashed).

The linear regression modeling showed a general pattern similar to that of CTS but with low slopes and low confidence. Yosemite toads moved shorter distances if they encountered the fence closer to the tunnel system and their initial direction was toward the tunnel system. There was no difference in predicted move distances for the toads that encountered the fence and turned in the "wrong" (away) direction (Figure 10).

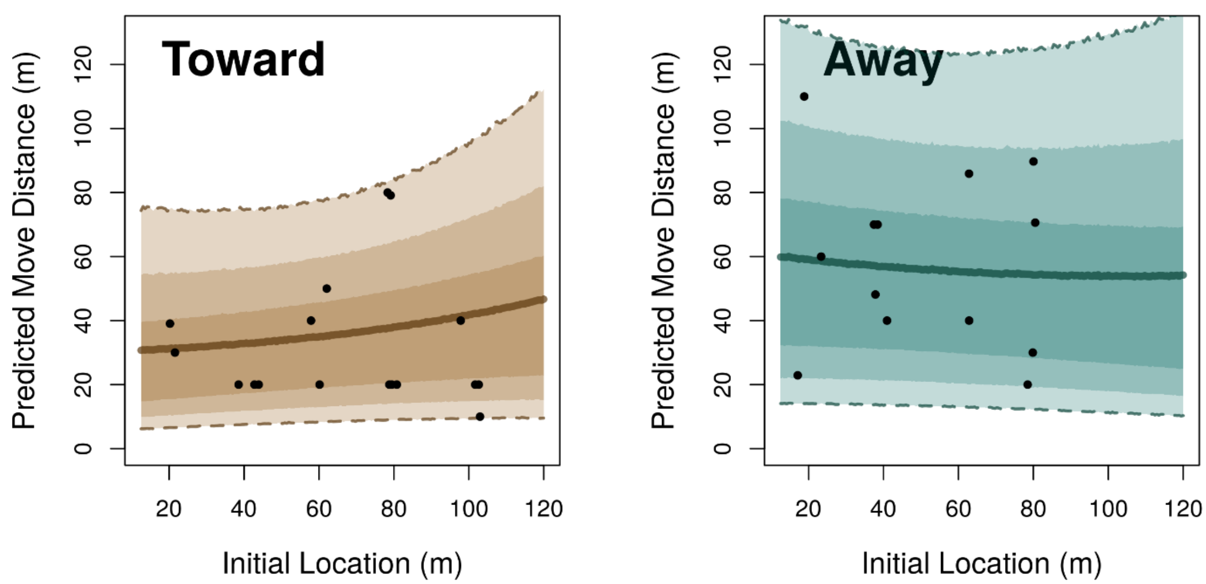

Figure 10. Movement Distance by Initial Location and Direction of Travel (Toward or Away from Underpass) with 90% Confidence Intervals.

The probability that Yosemite toads reached the tunnel system (0 m camera) decreased rapidly with increasing distance from the ERS system and was also highly dependent upon their initial direction choice. Yosemite toads had a high probability of reaching the ERS underpass if they encountered the fence at a distance of 20 m (mesh fencing) to 40 m (solid fencing) and were moving toward the ERS. Probabilities rapidly declined beyond those distances and were low if the toads were moving away from the ERS (Table 2, Figure 11). The estimates close to 1.0 and 0.0 indicated more data is needed to more accurately predict the probabilities of success in this system.

Table 2. Probability of Reaching Underpass by Initial Location, Direction of Travel (Toward or Away from Underpass), and Fence Type.

	Solid Fencing				Mesh Fencing			
	TOWARD Underpass		AWAY from Underpass		TOWARD Underpass		AWAY from Underpass	
Initial Location (m)	Probability of Success	90% CI	Probability of Success	90% CI	Probability of Success	90% CI	Probability of Success	90% CI
10	1.00	1.00- 1.00	.48	.21- .75	1.00	.99- 1.00	.01	.00- .06
20	1.00	1.00- 1.00	.44	.20- .70	.91	.41- 1.00	.01	.00- .05
40	.65	.00- 1.00	.37	.14- .63	.02	.00- .11	.01	.00- .04
60	.04	.00- .27	.32	.07-.63	.00	.00- .00	.01	.00- .03
80	.00	.00- .00	.28	.04-.68	.00	.00- .00	.00	.00- .02
100	.00	.00- .00	.25	.01-.72	.00	.00- .00	.00	.00- .02

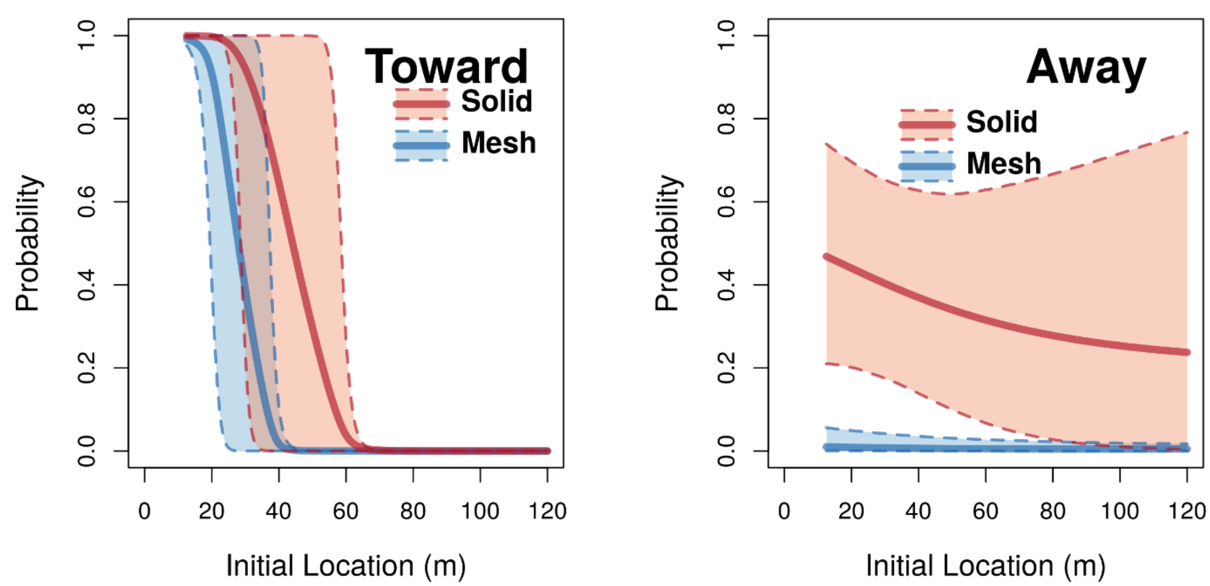

Figure 11. Probability of Reaching Underpass by Initial Location, Direction of Travel (Toward or Away from ERS), and Fence Type with 90% Confidence Intervals. Note that more samples are needed to better inform the models.

Underpass Permeability

Of the eight Yosemite toads that were tracked moving toward the ERS system at one of the "0 m" cameras (~5 m from the ERS entrance), three moved underneath at the first immediate right/left turn from the barrier fencing into the ERS and two moved along the length of the ERS (not underneath) to the barrier fencing on the other side. It is possible the other three toads moved under the bridge but not across a HALT trigger. Toads were detected on the time lapse cameras during the periods of their activity but could not be identified to individual.

Twenty-four other Yosemite toads that moved under the ERS were detected by one of the two HALT triggers (16 toads) or by a time lapse camera (8 toads). These data represent only a subsample of available linear width of the ERS system, so we suspect many more Yosemite toads passed under the crossing. At an average movement speed of 1 m/min and a field of depth of about 1 m, we estimate the eight time-lapse cameras subsampled toads across approximately 40% of the linear length of the ERS for 20% of the time. Because of this, we expect the total number of toads that moved under the ERS was likely closer to 100 during the time periods monitored.

The relative activity of Yosemite toads immediately inside vs. outside (~5 m from opening) of the ERS crossing system was almost equal (20 vs. 19 events; Table 3). The relative activity of other animals varied by species and groups. In general, mammals were detected at greater rates underneath vs. outside the ERS system (ratio 3.1), while reptiles and amphibians were detected at slightly lower rates underneath vs. outside the ERS system (ratios 0.70 and 0.83).

			RELATIVE ACTIVITY		
			Outside	Inside	Ratio
AMPH	Pacific Treefrog	*Hyla regilla*	209	174	0.83
	Yosemite Toad	***Anaxyrus californica***	**20**	**19**	0.95
	Sierra Nevada Ensatina	*Ensatina eschscholtzii platensis*	12	4	0.33
	Unknown salamander		0	3	na
		Subtotal Amphibians	241	200	0.83
REPT	Mountain Gartersnake	*Thamnophis elegans elegans*	25	14	0.56
	Rubber Boa	*Charina bottae*	6	4	0.67
	Sierra Alligator Lizard	*Elgaria multicarinata*	6	7	1.17
	Western Fence Lizard	*Sceloporus occidentalis*	6	2	0.33
	Unknown lizard		1	4	4.00
		Subtotal Reptiles	44	31	0.70
MAMMALS	Mice/Rats	*Family Rodentia*	165	534	3.24
	CA ground squirrel	*Otospermophilus beecheyi*	19	38	2.00
	Long-tailed Weasel	*Mustela frenata*	0	1	>1.0
	Spotted skunk	*Spilogale putorius*	0	4	>1.0
	American marten	*Martes americana*	0	2	>1.0
	Chipmunk	*Neotamias spp.*	3	1	0.33
	CA Vole	*Microtus californicus*	2	1	0.50
	Shrew	*Sorex spp.*	1	16	16.00
	Yellow-bellied Marmot	*Marmota flaviventris*	1	1	1.00
		Subtotal Mammals	191	598	3.13

Table 3. Relative Activity by Species Immediately Inside vs. Outside Elevated Road Segment.

Discussion

Although the sample size was low due to seasonal weather and sampling constraints, we found similarities between the fence movement behavior of Yosemite toads and CTS (Chapter 4). On average, Yosemite toads moved a distance of 52 m along barrier fencing before "giving up" and their probability of making it to the crossing decreased rapidly with increasing distance from the ERS. This is very close to the 50 m average that Ottberg and van der Grift (2019) reported for *Bufo bufo* in the Netherlands. Many individuals moved back and forth along the fencing and the average of 52 m represents the average span of total fence distance moved. Therefore, approximately half moved greater distances and half moved smaller distances with approximately 90% of toads estimated to move 20 m or more. Because our cameras were set 20 m apart, we were unable to estimate the specific distances with high confidence. However, these preliminary results suggest that passages spaced within 20 m of one another along Yosemite toad migratory pathways should provide connectivity to 90% of the population.

As with CTS, the likelihood that only some animals will reach a passage informs planning and monitoring of crossing systems for migratory amphibians and other migratory species. Without considering this in planning for distances between crossings, there is a potential for crossing systems constructed to reduce road mortality to become a barrier to population level movements.

In addition to distance moved, the direction Yosemite toads turned when reaching the barrier fencing was a large factor in whether they reached the crossing. Toads that reached the barrier fencing and then travelled in the wrong direction (away from the tunnels) were significantly less likely to reach the crossing than toads that made the correct initial direction choice. In fact, it appeared that, as with CTS, toads that made the correct initial direction choice were also more likely to travel longer distances to reach the tunnels.

It is possible that not all Yosemite toads were making migratory movements during our study, as they may have been foraging. However, in that case we would expect to document the same individuals on multiple dates along the fence line which was rare in our study.

The transparency of fencing (mesh vs. solid) did not significantly affect the movement distances or probability of making it to the underpass system, although the estimated probabilities were slightly less for the semi-transparent fencing. Unlike CTS, there was no apparent difference in speed or turnaround rates (moving back and forth) by fence type in the preliminary data for Yosemite toads.

We caution that a greater sample size is needed to accurately predict the probability of success by initial distance from passage, direction choice, and effects of fence type and age class on Yosemite toad movements along the fence lines. Continued data collection in future years and placement of additional cameras at 10 m along the fence lines will allow for higher confidence in these estimates.

Finally, initial results showed that the ERS crossing has a high potential to provide increased connectivity for Yosemite toads and a wide range of other amphibian, reptile, and small mammal species while greatly reducing road mortality (no road mortality of Yosemite toads has been documented in the project footprint since installation of the ERS; S. Barnes, USFS, pers.

comm.). This new prototype crossing can be made to any length, creating a wide passage without constricting migratory movements to small tunnels. The prototype ERS also allows natural light, moisture and rainfall to permeate the length of the passage so that climate and moisture underneath is similar to that outside. The large width of the passage does present challenges in monitoring successful crossings due to the wide monitoring area. We are exploring the use of different camera systems, additional cameras, and wildlife tracking techniques to better monitor movements near and underneath the passage in the future.

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References

Andrews KM, P Nanjappa and SP Riley (eds), 2015a. Roads and ecological infrastructure: concepts and applications for small animals. JHU Press, Baltimore, MD.

Andrews KM, TA Langen and RPJH Struijk. 2015b. Reptiles: Overlooked but often at risk from roads. Handbook of Road Ecology. Wiley, New York, pp. 271–280.

Brehme, CS, SA Hathaway, and RN Fisher. 2018. An objective road risk assessment method for multiple species: ranking 166 reptiles and amphibians in California. Landscape Ecology 33(6): 911–935.

Davidson C and GM Fellers. 2005. *Bufo canorus*. In: Lannoo M (ed) Amphibian declines: the conservation status of United States species. University of California Press, Berkeley, pp. 430–432.

Drost, CA and GM Fellers. 1996. Collapse of a regional frog fauna in the Yosemite area of the California Sierra Nevada, USA. Conservation Biology 10: 414–425.

Eigenbrod F, SJ Hecnar and L Fahrig. 2008. The relative effects of road traffic and forest cover on anuran populations. Biological Conservation 141(1): 35–46.

Forman RT, D Sperling, JA Bissonette, AP Clevenger, CD Cutshall, VH Dale, L Fahrig, R France, CR Goldman, K Heanue and JA Jones. 2003. Road ecology. Science and Solutions. Island Press, Washington.

Glista DJ, TL DeVault and JA DeWoody. 2008. Vertebrate road mortality predominantly impacts amphibians. Herpetological Conservation and Biology 3(1): 77–87.

Hamer, AJ. and MJ McDonnell. 2008. Amphibian ecology and conservation in the urbanising world: a review. Biological Conservation 141(10): 2432–2449.

Hammerson, G, R Grasso and C Davidson. 2004. *Anaxyrus canorus*. The IUCN Red List of Threatened Species 2004: e.T3180A9659674. *https://dx.doi.org/10.2305/IUCN.UK.2004.RLTS.T3180A9659674.en.* Downloaded on 28 May 2020.

Hobbs, MT and CS Brehme. 2017. An improved camera trap for amphibians, reptiles, small mammals, and large invertebrates. PLOS ONE 12(10), p.e0185026.

Jennings, MR and MP Hayes. 1994. Amphibian and reptile species of special concern in California (p. 255). Rancho Cordova, CA: California Department of Fish and Game, Inland Fisheries Division.

Milburn-Rodríguez JC, J Hathaway, K Gunson, D Moffat, S Béga and D Swensson. 2016. Road mortality mitigation: The effectiveness of Animex fencing versus mesh fencing. *https://animexfencing.com/whyanimex/animex-vs-mesh*.

Orłowski G. 2007. Spatial distribution and seasonal pattern in road mortality of the common toad *Bufo bufo* in an agricultural landscape of south-western Poland. Amphibia-Reptilia 28(1): 25–31.

Ottburg, FG and EA van der Grift. 2019. Effectiveness of road mitigation for common toads (*Bufo bufo*) in the Netherlands. Frontiers in Ecology and Evolution 7: 23.

Hamer, AJ and McDonnell, MJ, 2008. Amphibian ecology and conservation in the urbanising world: a review. Biological Conservation 141(10): 2432–2449.

Rasband, WS. 1997–2018. ImageJ,. US. National Institutes of Health, Bethesda, Maryland, USA, *https://imagej.nih.gov/ij/.*

Rytwinski T and L Fahrig. 2012. Do species life history traits explain population responses to roads? A meta-analysis. Biological Conservation 147(1): 87–98.

Semlitsch, RD. 2008. Differentiating migration and dispersal processes for pond-breeding amphibians. Journal of Wildlife Management 72(1): 260–267.

Shaffer, HB and GM Fellers, A Magee and SR Voss. 2000. The genetics of amphibian declines: population substructure and molecular differentiation in the Yosemite toad *Bufo canorus* (Anura, Bufonidae) based on the single-strand conformational polymorphism analysis (SSCP) and mitochondrial DNA sequence data. Molecular Ecology 9: 245–257.

Trenham PC, WD Koenig, MJ Mossman, SL Stark and LA Jagger. 2003. Regional dynamics of wetland-breeding frogs and toads: turnover and synchrony. Ecological Applications 13(6): 1522–1532.

U.S. Fish and Wildlife Service. 2014. Endangered Species Status for Sierra Nevada Yellow-Legged Frog and Northern Distinct Population Segment of the Mountain Yellow-Legged Frog, and Threatened Species Status for Yosemite Toad; Final Rule. Federal Register, Vol. 29, No. 82, April 29, 2014. 81 FR 59045 59119.

Van Tienhoven AM, JE Den Hartog, RA Reijns and VM Peddemors. 2007. A computer-aided program for pattern-matching of natural marks on the spotted ragged tooth shark *Carcharias taurus*. Journal of Applied Ecology 44, 273–280. *https://reijns.com/i3s/.*

Chapter 6. Effect of Fence Opacity on the Movement of Reptiles and Amphibians and the Effectiveness of Two Jump-out Designs.

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Introduction

Options for road barrier materials vary greatly from solid concrete, composites, and plastics to transparent and semi-transparent wire and plastic meshes. Meshes are typically easy to work with and are permeable to water and air movement; however, there is some evidence that animals may spend more time trying to climb or get through transparent fencing than solid fencing (Milburn-Rodriguez et al. 2016). Thus, opacity could influence both barrier effectiveness and the probability and speed with which an animal finds a wildlife crossing.

"Jump-outs" are commonly built along road barrier fencing to ensure that large animals can escape if they get caught within the road barrier sections (Clevenger and Huijser 2011, van der Ree et al. 2015, Hopkins et al. 2018). However, few jump-outs have been designed, tested, or used for allowing the escape of herpetofauna back into the habitat if they become trapped along a road with barrier fencing on both sides.

We conducted studies at the Rancho Jamul Ecological Reserve (RJER) in Jamul, California, to compare the behavior and movement speed of herpetofauna in relation to transparent, semi-transparent, and solid fencing. In addition, we tested the effectiveness of two jump-out designs. The results of these studies will help to inform transportation agencies on these important components of road barrier and crossing systems.

Herpetofauna Groups Targeted: Snakes, lizards, toads

Research questions:

1. Are transparent, semi-transparent mesh, and solid barriers equally effective as barriers to movement?
2. How quickly do individuals travel along barriers of differing opacity?
3. Are jump-outs of differing designs effective in allowing herpetofauna to escape if trapped within the roadway?

Methods

Field Study

At Rancho Jamul Ecological Reserve, we set up a multi-faceted fenced enclosure to study the behavior and speed of animals along different fence materials and the effectiveness of jump-outs (Figure 1). The fenced behavioral enclosure was installed along a habitat edge between riparian scrub and coastal scrub habitat in the reserve. The behavioral enclosure consisted of a 12 m long, 45 cm wide linear "runway" with 2 m long alternating segments of hardware cloth, black plastic mesh (ERTEC® rigid polymer matrix fence with climbing barrier at top), and solid black

(Animex® high-density polyethylene (HDPE-2)) barrier fencing 60 inches in original height buried to a depth of 10–15 cm. The alternating segments contained the same barrier fencing on both sides of the runway and each fence type was randomly repeated two times along the runway. To prevent bias based upon the location of the fencing, the order of the fencing types was changed during the middle of the study. The bare soil floor of the enclosure was tamped down with a steel dirt tamper to prevent digging and hiding behaviors. We also buried 1 in. PVC pipes ¾ in. deep along the floor in between each fence segment perpendicular to the runway to provide a white strip between segments. This allowed us to easily discern when an animal moved from one segment to another.

We built a 4 m introduction section made of white solid fencing for introduction and habituation of test animals before they made the decision to start moving along the test runway. At the end of the runway, we built an exit section with four jump outs. Two "high" jump outs were built as earthen ramps leading up to the top of the fence, with an approximate 50 cm drop to jump out into the habitat. Two "low" jump-outs were modified rectangular cones (ERTEC®) with a diameter of 22 cm installed halfway up the barrier fencing with a small earthen ramp and an approximate 20 cm drop into the habitat (Figure 2). The cones were modified by increasing the size of the opening on the exit side to a diameter of approximately 10 cm. An outer fence around the exit section allowed us to capture animals once they exited the jump-out and return them to the original place of capture. The entire behavioral enclosure was covered on top at a height of approximately 1.5 m with shade sail cloth to prevent spots of sunlight and shade from influencing animal behaviors.

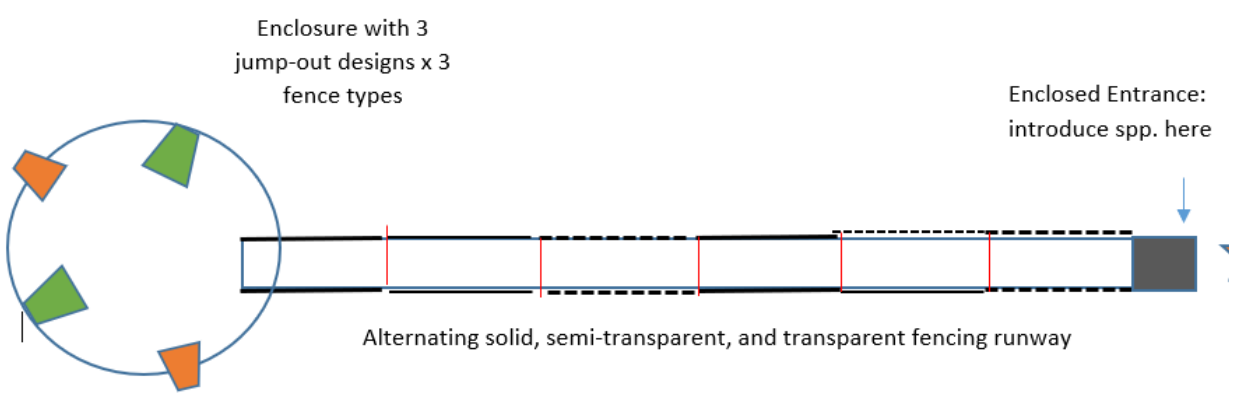

Figure 1. Graphic of Behavioral Enclosure

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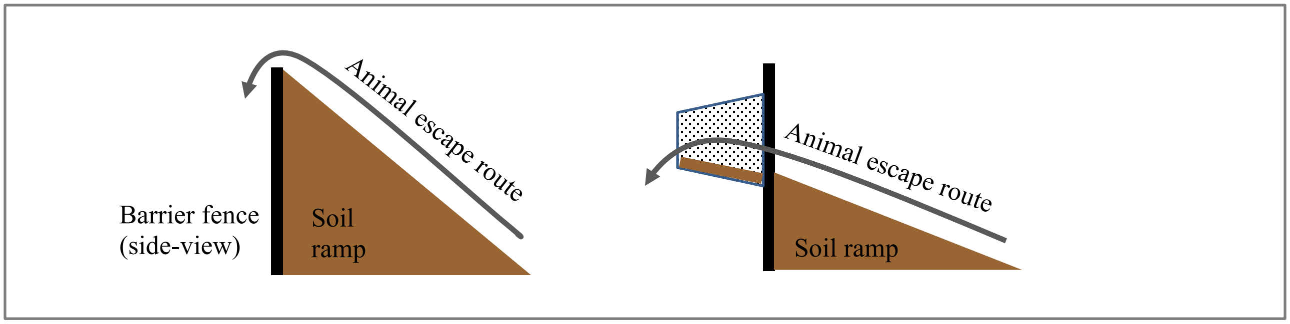

Figure 2. Diagram of Jump-Out Configurations a) Over Fence and b) Through Fence.

Trials were run in spring and summer months from June through September in 2018 and March through June in 2019. To determine if animals would respond differently to the transparent and semi-transparent fencing in the presence of a visual barrier, from late August through September of 2018 and June of 2019, we placed black duct tape along the bottom of the first segments of hardware cloth and mesh fencing approximately 15 cm (6 in.) in height.

We captured animals using visual searching and linear trap arrays with pitfall traps and snake traps within 150 m of the behavioral enclosure as described in Fisher et al. (2008). The traps were set in the early morning, checked throughout the day, and closed at mid-day. Some snakes were also opportunistically collected if observed while checking the pitfall arrays. Each animal included in the trials was weighed, measured, temporarily marked with ink (Sharpie®), placed into a holding bag (snake bag/pillowcase) and brought to the enclosure.

Captured animals were placed one at a time within the introduction section approximately 2 m from the first fence segment. Observers were stationed behind camouflage netting at the entrance and exit sides of the behavioral enclosure. The first observer on the exit side operated a stationary video camera on a tripod to record all animal movements within the enclosure and was behind camouflage netting throughout the entire trial. The second observer gently released each animal from its holding bag or snake trap into the enclosure approximately 2 m from the first fence trial segment while behind the camouflage netting. Each animal was then observed until it left the behavioral enclosure or for 30 minutes (if it did not complete the trial). Examples of reptiles moving through the enclosure are provided in Figure 3. After the trial, each animal was immediately released to its original place of capture. Once back at the field office, the observers uploaded videos and recorded the following:

- Direction and pathway of all movements
- Time spent along each fence segment
- Whether a solid visual barrier was present (on mesh or HC fencing)
- Behaviors observed at each fence segment: Poking, climbing, moving back and forth, sitting
- Number of fence segments completed
- Whether animals escaped by climbing over fencing
- What exits were approached and used

Figure 3. Photos of A) California Striped Racer (*Masticophis lateralis*) Poking at Hardware Cloth, B) Orange-Throated Whiptail (*Aspedoscelis hyperythrus*) Poking at Hardware Cloth, C) Rosy Boa (*Lichanura trivirgata)* Moving Through Runway Toward Exit Structures, D) Orange-Throated Whiptail Exiting High Ramp and E) Red-Diamond Rattlesnake (*Crotalus ruber*) Exiting Escape Funnel.

Analysis

Only data from individual animals that completed at least three fence segments (one of each type) were used in the analysis. Many animals turned around one or more times during their trial and travelled by the same fence lines on repeated occasions. We used all data where a complete pass was made and accounted for this with a covariate "FirstSegment" indicating whether it was the individuals first encounter with that fence type.

Movement Time along Fence Types: Logistic Regression:

We first modelled the probabilities of fence interaction behaviors using logistic regression. For this we only used the individuals first encounter with each fence type (Hardware Cloth, Mesh, Solid +/- Visual Barrier). To determine whether the probability of fence interaction behaviors differed across fence types and by taxonomic group (lizards, snakes, toads) and the effect of a visual barrier, we fitted a general linear model with a binomial distribution and logit-link function (Program R):

Fence Interaction Behavior (0/1) ~ FenceType*VisualBarrier + TaxonomicGroup

Movement Time along Fence Types: Linear Regression:

Individuals of different species and taxonomic groups had widely varying times along the fence lines within the behavioral enclosure. To minimize this variation and to determine whether speed of movement was affected by fence type, we did two things. First, we removed records of segment passes where the behavior "sitting" was recorded. This behavior was not considered an interaction with the fence but represented varying, and sometimes long, periods of time where an animal would "freeze." Second, we standardized all time data to z-distributions by individual (mean= 0, data as number of standard deviations from the mean). As an example, an individual with times of 5, 10, and 15 min across fences A, B, and C would be transformed to -1, 0, 1. Likewise, another individual with times of 1, 2, and 3 min across fences A, B, and C would be transformed to -1, 0, 1. This allowed us to account for the wide variability of speed among individuals and focus on their relative responses to the different fence types.

We then modelled the data using linear regression fitted by least squares to determine whether time differed across fence types and if the installation of a visual barrier affected time spent along the fence types by taxonomic group (lizards, snakes, toads)(Program R):

Standardized Time ~ FenceType*VisualBarrier + TaxonomicGroup + FirstSegment

For both types of models described, we also ran mixed model versions based on maximum likelihood with the individual as a random variable; the mixed models had convergence issues due to the large number of parameters (i.e. overparameterization). However, the model coefficients and standard error estimates were very similar between the general linear and mixed model types. Further analyses of this study will be conducted using Bayesian methods for a manuscript.

Results

We captured a total of 174 individuals to use in our trials. Of these, 66% (114) completed at least one full set of fence types and thus were used in the behavioral modelling. Eighty individuals completed moving through all fence lines to the exit arena and of these, 87.5% (70) exited using one of the jump-outs (Table 1).

Table 1. Numbers of Species Used in Trials with Outcomes

		Number	Fence lines passed (out of 6)			Number
Taxon	Species	Escaped	<3	3-5*	6*	exited
Frog	*SubTotal*			1		
	Pseudacris regilla			1		
Lizard	*SubTotal*		46	24	57	49
	Aspidoscelis hyperythrus		23	7	42	38
	Aspidoscelis tigris		1	2	2	2
	Elgaria multicarinata		2	1	2	1
	Sceloporus occidentalis		11	13	6	5
	Sceloporus orcutti				1	
	Uta stansburiana		9	1	3	2
	Plestiodon skiltonianus	1	1		0	
Snake	*SubTotal*		6	6	21	20
	Crotalus ruber				3	3
	Crotalus oreganus				2	2
	Lampropeltis getula				2	2
	Lichanura trivirgata				1	1
	Coluber fuliginosus				2	1
	Coluber lateralis		3	2	5	5
	Pituophis catenifer		2	3	5	5
	Tantilla planiceps		1		0	
	Thamnophis hammondii			1	2	2
Toad	*SubTotal*		6	3	2	1
	Anaxyrus boreas		2	2	2	1
	Spea hammondii		4	1	0	
	Grand Total	1	59	34	80	70

*used in modelling

All behavioral models showed that fence type was significant in predicting the probability that herpetofauna would exhibit fence interaction behaviors (Tables 2–4, Figures 4–6). Poking, moving back and forth, and climbing behaviors were more common as the transparency of the fence increased (solid > mesh> hardware cloth). Across taxonomic groups, toads showed higher probabilities of fence interaction behaviors than lizards and snakes, although the variability in the data was greater for toads. Along with the greater probability of these behaviors, the time it took for herpetofauna to pass each fence type increased as the transparency of the fence increased (Table 5, Figure 7).

The addition of a 15 cm (6 in) visual barrier along the bottom of the mesh and hardware cloth fencing reduced the probability of poking and back and forth movements among all taxa and was particularly significant in reducing poking behaviors of lizards and snakes. When a visual barrier was present, there was little difference in the probability of fence interaction behaviors among the fence types. Similarly, a visual barrier significantly reduced the time it took for individuals to move along the mesh and hardware cloth fencing so that there was little difference in individual speed among all fence types.

Table 2. Effect of Fence Type on Animal Behavior: Poking and Looking

Coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept= Solid)	-3.215	0.412	-7.811	5.65E-15	***
FenceTypeMesh	2.482	0.425	5.847	5.01E-09	***
FenceTypeHC	3.582	0.430	8.325	< 2e-16	***
VB011	-1.228	1.150	-1.067	0.286	
TypeSnake	0.281	0.262	1.074	0.283	
TypeToad	3.044	0.734	4.150	3.32E-05	***
FirstSegType1	0.232	0.252	0.918	0.359	
FenceTypeMesh:VB011	-0.885	1.313	-0.674	0.500	
FenceTypeHC:VB011	-0.640	1.236	-0.518	0.604	

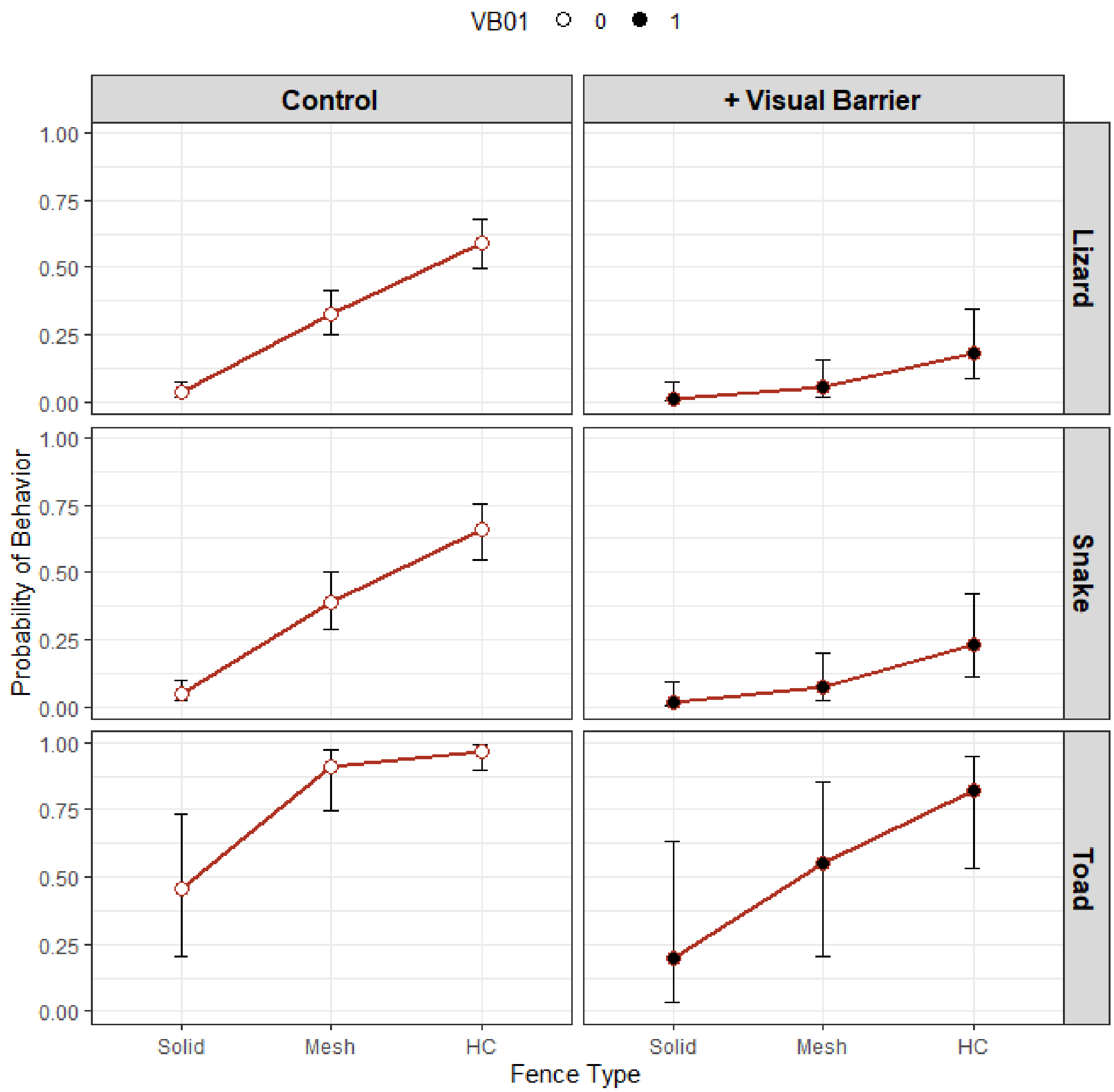

Figure 4. Effect of Fence Type on Animal Behavior: Poking and Looking

VB= visual barrier, HC= hardware cloth

Table 3. Effect of Fence Type on Animal Behavior: Back and Forth Movements

Coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept= Solid)	-2.928	0.418	-7.001	2.53E-12	***
FenceTypeMesh	1.606	0.452	3.552	3.83E-04	***
FenceTypeHC	2.245	0.444	5.053	4.36E-07	***
VB011	-0.715	1.102	-0.649	0.516	
TypeSnake	-0.752	0.338	-2.225	0.026	*
TypeToad	1.076	0.742	1.451	0.147	
FirstSegType1	0.075	0.284	0.265	0.791	
FenceTypeMesh:VB011	0.020	1.235	0.016	0.987	
FenceTypeHC:VB011	-1.265	1.334	-0.948	0.343	

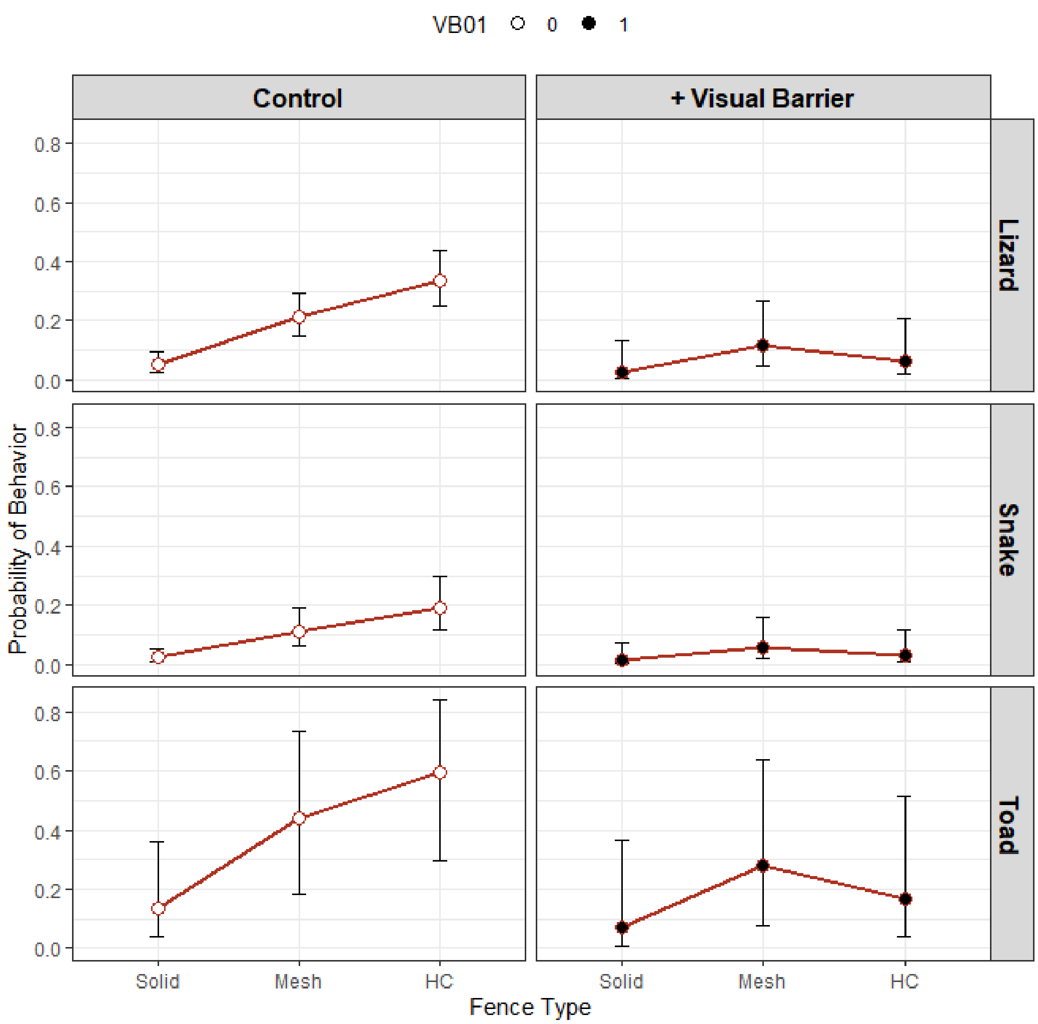

Figure 5. Effect of Fence Type on Animal Behavior: Back and Forth Movements

VB= visual barrier, HC= hardware cloth

Table 4. Effect of Fence Type on Animal Behavior: Climbing

Coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept= Solid)	-3.319	0.521	-6.373	0.000	***
FenceTypeMesh	1.105	0.576	1.917	0.055	.
FenceTypeHC	1.662	0.561	2.963	0.003	**
VB011	-16.458	1711.284	-0.010	0.992	
TypeSnake	-1.850	0.745	-2.484	0.013	*
TypeToad	2.020	0.790	2.558	0.011	*
FirstSegType1	0.102	0.390	0.261	0.794	
FenceTypeMesh:VB011	-0.938	2465.362	0.000	1.000	
FenceTypeHC:VB011	14.523	1711.284	0.008	0.993	

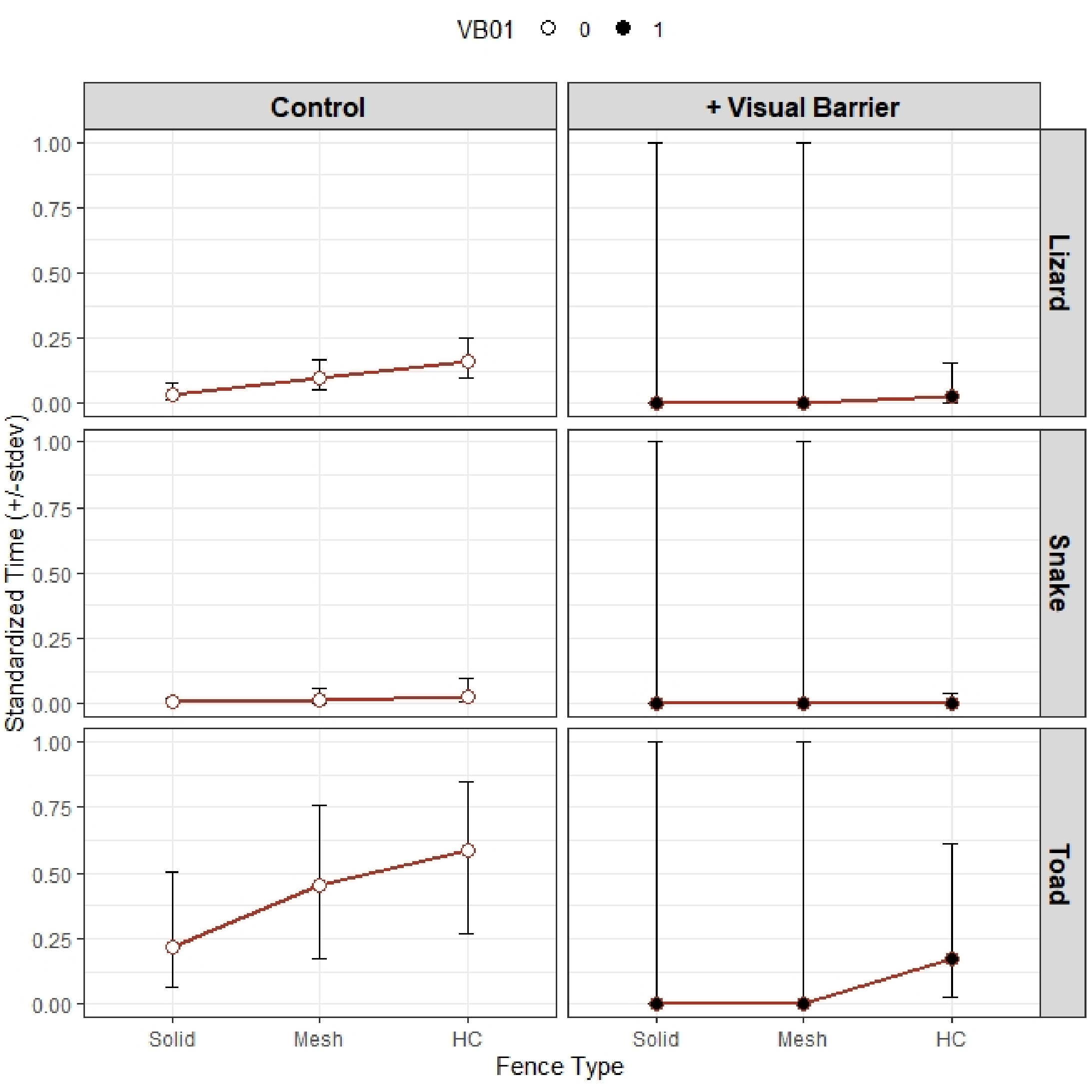

Figure 6. Effect of Fence Type on Animal Behavior: Climbing

VB= visual barrier, HC= hardware cloth

Table 5. Effect of Fence Type on Relative Movement Time

Coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept= Solid)	-0.31719	0.06641	-4.776	2.11E-06	***
FenceTypeMesh	0.24439	0.09012	2.712	0.00683	**
FenceTypeHC	0.72434	0.09106	7.955	5.71E-15	***
VB011	0.56038	0.1081	5.184	2.72E-07	***
TypeSnake	0.04315	0.08091	0.533	0.59394	
TypeToad	-0.02768	0.17773	-0.156	0.87626	
FirstSegType1	-0.13039	0.07296	-1.787	0.07427	.
FenceTypeMesh:VB011	-0.4652	0.16574	-2.807	0.00512	**
FenceTypeHC:VB011	-1.01179	0.15753	-6.423	2.22E-10	***

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

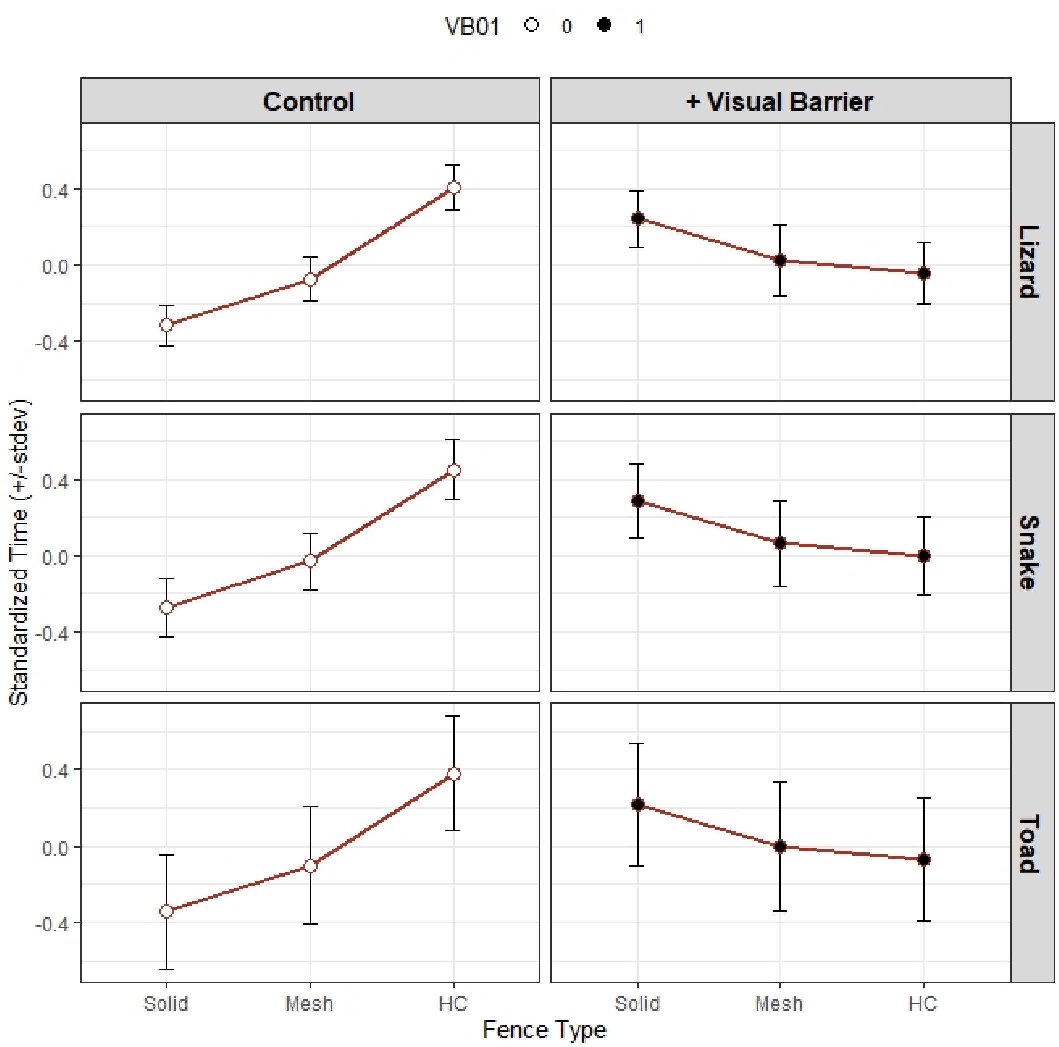

Figure 7. Effect of Fence Type on Relative Movement Time

Effectiveness of jump-outs

A total of 75% of lizards (43/57), 95% of snakes (20/21), and 50% of toads (1/2) used a jump-out to escape the enclosure. There was little difference between the use of the high ramp and low funnel jump-outs by lizards and snakes (Figure 8). We observed that lizards often sat on top of the high ramp for long periods of time before jumping to the ground, whereas there was little hesitation with the low jump-outs. A higher proportion of lizards (16–23%) did not exit via the jump-outs. Many of these sat in the exit arena until they timed out or moved back in the direction of the entrance.

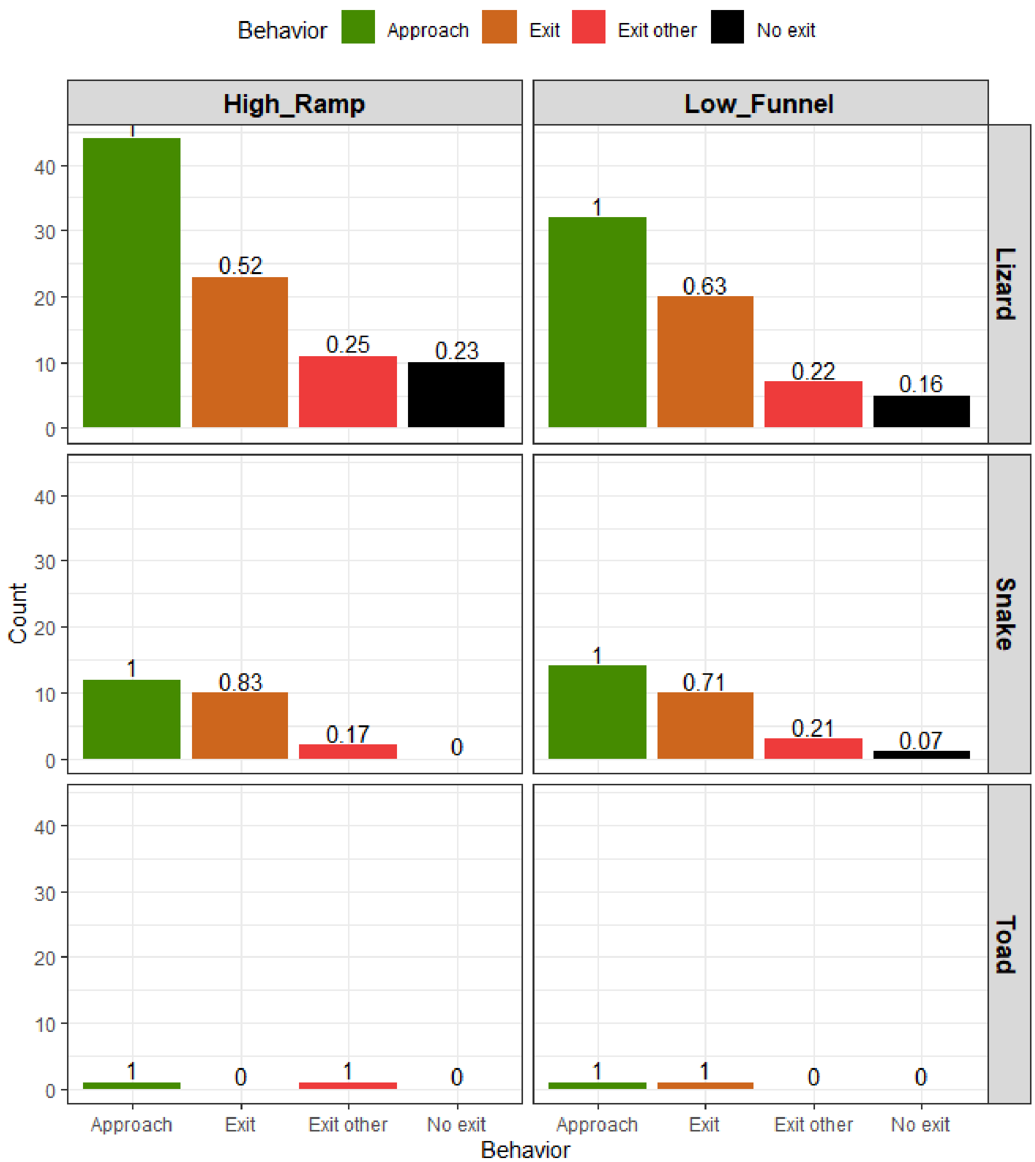

Figure 8. Proportion of Herpetofauna Groups that Approached and Used 2 Jump-Out Designs.

Discussion

Our results provide evidence that herpetofauna are more likely to interact with the transparent and semi-transparent fences by poking it with their noses, pacing back and forth, and attempting to climb. The transparent and semi-transparent fencing types used in this study are not only see-through but are permeable to the movement of air. Because sight and chemoreception senses are typically well developed in reptiles, it is not clear to what extent these different senses are driving fence interaction behaviors. However, animals exhibiting these behaviors appear to be trying to find a way through the fence to the other side.

Although fence interaction behaviors have been documented elsewhere in comparing hardware cloth and solid fencing (Ruby et al. 1994, Milburn-Rodríguez et al. 2016), our study shows a gradation of response from solid to semi-transparent to transparent fencing in all taxa studied. In addition, our study shows that these behaviors result in animals moving slower, or spending more time, along transparent/permeable fencing in comparison to solid fencing. This may not be a concern when the purpose of the fence is primarily to exclude animals. However, effect of fence opacity on movement rates should be considered when a dual objective is to lead species toward a road crossing structure, particularly when high permeability and population connectivity across the structure is desired (Simlitsch 2008, Hamer et al. 2015, Brehme et al. 2018).

There are reasons why hardware cloth, mesh, or solid barriers may be desirable in particular landscapes, habitats, and climates with considerations that include rain and wind permeability, durability, and aesthetics (Langton and Clevenger 2021). Our study is the first to show that addition of a simple visual barrier at ground level (6 inches our study) can result in substantial decreases in fence interaction behaviors and in increased rates of movement. For most response measures, herpetofauna responses to mesh and hardware cloth fencing with a visual barrier were not significantly different than to the solid barrier. This may allow for more flexibility in the decision-making and planning processes for barrier systems for herpetofauna. With any barrier or fencing system, proper maintenance is extremely important for its continued success (Hamer et al. 2015, Baxter-Gilbert et al. 2015, Langton and Clevenger 2021).

Finally, we showed that two jump-out configurations were largely effective in allowing animals trapped on the wrong side of the barriers to escape back into the habitat. Animals can easily get trapped on the wrong (road) side of barrier fencing by entering through a tear or opening in the fencing or by entering the roadway at the end of the exclusion fencing. Although jump-outs are commonly built structures along wildlife fencing for large mammals, they have not commonly been incorporated into transportation planning for small animal barriers. Jump-outs for herpetofauna can be provided at regular intervals along barriers with interval distances determined by target species movement distances. It is also important that any jump-out design for herpetofauna consider the safety of other wildlife. For short barrier fencing, most other wildlife can simply jump over the barrier. For larger barrier systems, escape routes may include multiple size jump-outs for a wider variety of species.

Acknowledgements

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References

Baxter-Gilbert, JH, JL Riley, D Lesbarrères and JD Litzgus. 2015. Mitigating reptile road mortality: fence failures compromise ecopassage effectiveness. PLOS ONE 10(3), p.e0120537.

Brehme CS, SA Hathaway and RN Fisher. 2018. An objective road risk assessment method for multiple species: Ranking 166 reptiles and amphibians in California. Landscape Ecology 33(6): 911–935.

Clevenger, AP and MP Huijser. 2011. Wildlife Crossing Structure Handbook, Design and Evaluation in North America, Publication No. FHWA-CFL/TD-11-003. Department of Transportation, Federal Highway Administration, Washington D.C., USA.

Fisher, R, D Stokes, C Rochester, C Brehme, S Hathaway and T Case. 2008. Herpetological monitoring using a pitfall trapping design in southern California. U.S. Geological Survey Techniques and Methods Vol. 2:A5. *https://pubs.usgs.gov/tm/tm2a5/pdf/tm2a5.pdf.*

Hamer, AJ, TE Langton, and D Lesbarrères. 2015. Making a safe leap forward: mitigating road impacts on amphibians. Handbook of road ecology, Van Der Ree, R, DJ. Smith, and C Grilo (eds). Handbook of Road Ecology. John Wiley & Sons, pp. 261–270.

Hopkins, CB, JS Johnson, SR Kuchta, , DS McAvoy, VD Popescu, SC Porter, WM Roosenburg, GP Sisson, BR Sperry, MT Trainer and RL Wiley. 2018. Effectiveness of Wildlife Mitigation Treatments along the Nelsonville Bypass (No. FHWA/OH-2018-8).

Langton, TES, and AP Clevenger. 2021. Measures to Reduce Road Impacts on Amphibians and Reptiles in California. Best Management Practices and Technical Guidance. Prepared by Western Transportation Institute for California Department of Transportation, Division of Research, Innovation and System Information.

Milburn-Rodríguez JC, J Hathaway, K Gunson, D Moffat, S Béga and D Swensson. 2016. Road mortality mitigation: The effectiveness of Animex fencing versus mesh fencing. *https://animexfencing.com/whyanimex/animex-vs-mesh*.

Ruby, DE, JR Spotila, SK Martin and SJ Kemp. 1994. Behavioral responses to barriers by desert tortoises: implications for wildlife management. Herpetological Monographs 8: 144–160.

Semlitsch, RD. 2008. Differentiating migration and dispersal processes for pond-breeding amphibians. Journal of Wildlife Management 72(1): 260–267.

van der Ree, R, JW Gagnon and DJ Smith. 2015. Fencing: a valuable tool for reducing wildlife-vehicle collisions and funneling fauna to crossing structures. Handbook of Road Ecology. Oxford: John Wiley & Sons, pp. 159–171.

Chapter 7. Effectiveness of Turnarounds in Changing the Trajectory of Reptiles and Amphibians in San Diego, CA.

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Introduction

It is common practice to install 'turnarounds' at fence ends and where barriers are unable to span across private road entries and easements (e.g. Clevenger and Huijser 2011, Ontario Ministry of Natural Resources and Forestry 2016, Langton and Clevenger 2021). For this, road barriers end in a "U" shape and are designed to redirect animals back in the opposite direction at fence ends and keep them off the roadway. Although they are recommended in many countries and in guidance documents (e.g. Iuell et al. 2003, Clevenger and Huijser 2011, Gunson et al. 2016), there are no systematic studies to our knowledge that have addressed the relative effectiveness of turnarounds (Langton and Clevenger 2017).

We conducted studies at the Rancho Jamul Ecological Reserve in Jamul, California to test the effectiveness of turnarounds in changing the trajectory of movement for herpetofauna and small mammals. We also compared effectiveness and time spent within the turnarounds based upon fence type: transparent, semi-transparent, and solid fencing. The results of these studies will help to inform transportation agencies on these important components of road barrier and crossing systems.

Research questions:

1. Are fence end turnarounds effective in redirecting the trajectory of animal movement?
2. Is the effectiveness of turnarounds influenced by the opacity of barrier fencing?

Methods

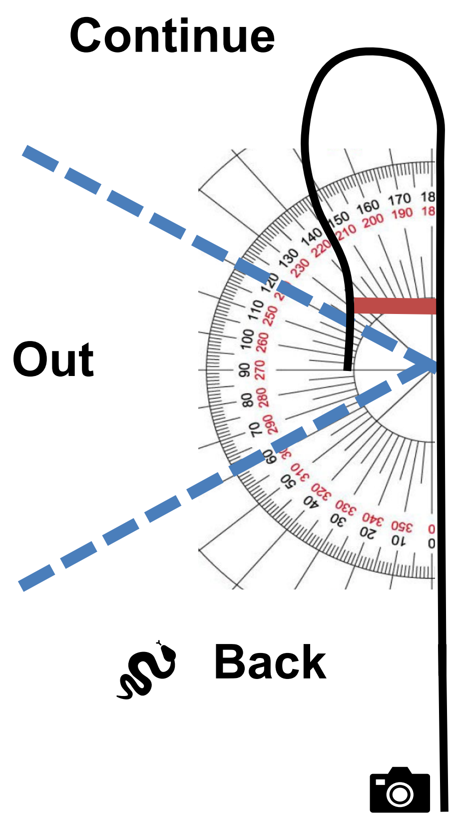
We installed three 20 m segments of solid barrier fencing within coastal sage scrub habitat in RJER adjacent to a dirt road. At the ends of each segment, we installed another 4 m of fencing and a turn-around approximately 1.5 m long and 1 m wide. The turnarounds ended approximately 0.4 m from the fence lines and extended another 0.4 m parallel to the fence (Figure 1). We used three materials with increasing opacity; hardware cloth (0.25 inch), mesh (ERTEC® rigid polymer matrix E-Fence), or solid fencing (Animex® high-density polyethylene (HDPE-2)). The placement of the turnarounds was mixed so that each segment ended with two of the different fence type materials. At the opening of each turnaround, we installed a HALT® active infrared trigger and camera system that allowed us to document animals going into and out of the turnarounds, as well as determine their trajectory upon leaving the turnaround. The cameras were placed 4.25 m from the end of the turnaround (2.25 m from trigger) with a frame of view that allowed us to follow the movement of animals for approximately 1 m in any direction and were set to record video for 25 seconds upon an animal activating the trigger. Cameras were set with 32-64GB SD cards and left on and checked on a weekly or biweekly basis from March 1 to Sept. 8, 2019.

Analysis

We watched all videos and recorded the following:

- Turnaround Fence Type and Segment number
- Species
- Time of entry and exit
- Distance and direction of travel

Individuals were only included in the analysis if the animals moved at least 0.7 m away from the end of the turnaround. If the same individual moved in and out of the turnaround more than once, only their final trajectory was recorded. Final direction of travel was recorded as three categories: Continue, Out, and Back (Figures 1 and 2). We also did not include data where an individual encountered another individual that may have affected the direction of travel.



Note: Extra stakes in ground to keep cows away from turnaround

Figure 1. Example of A) Turnaround with Camera and Trigger Set Up and B) Direction of Movement Categories.

Figure 2. Example of A) Cottontail Rabbit (*Sylvilagus audubonii*) Continuing in the Same Direction, B) Red-Diamond Rattlesnake (*Crotalus ruber*) Moving Away into the Habitat, and C) Western Toad (*Anaxyrus boreas*) Moving Back along the Fenceline after Leaving the Turnaround. Screenshots taken from Videos Showing Animals Continuing in the Same Direction Out of View.

To determine if the turnarounds were successful in changing the trajectory of movement among taxonomic groups and fence types, we analyzed the choice made by each subject after they reached the turnaround using a multinomial logit choice model (Figure 3). Each individual had a choice of turning back (1, "back"), exiting out of the structure (2, "out"), or continuing in the same direction of travel (3, "continue"). This model is a multinomial generalization of the logistic model which models a binomial response (with one trial, hence a Bernoulli random variable). For each choice, we first calculate a "probability potential." The first choice (back) is a "reference" and is assigned a probability potential of "1" in all cases. The remaining two responses have probability potentials that are an exponential (i.e. rate = exp(y)) function of the linear component of the model that depend on two predictor variables that encode fence type and three variables for taxonomic group, a response-specific intercept and two regression coefficients. The final probabilities for each choice were calculated as the probability potential for that choice divided by the sum of all the probability potentials. This ensured that sum of the probabilities for the choice made for each observation added to one. The taxon-specific parameters were drawn from normal distributions with means and precisions based on parameters drawn from "all taxa" hyper-prior distributions. The hyperprior means were drawn from a normal distribution with mean 0 and 0.001 precision. The precisions were calculated as one over a squared standard deviation, with the standard deviation drawn from a uniform distribution on an interval from 0 to 1000. The parameters were sampled from their posterior distributions using MCMC (as described above) and described by mean, median, and quantiles of their marginal distributions. This allowed us to assess the effect of turn around fence type on the choice made by each subject.

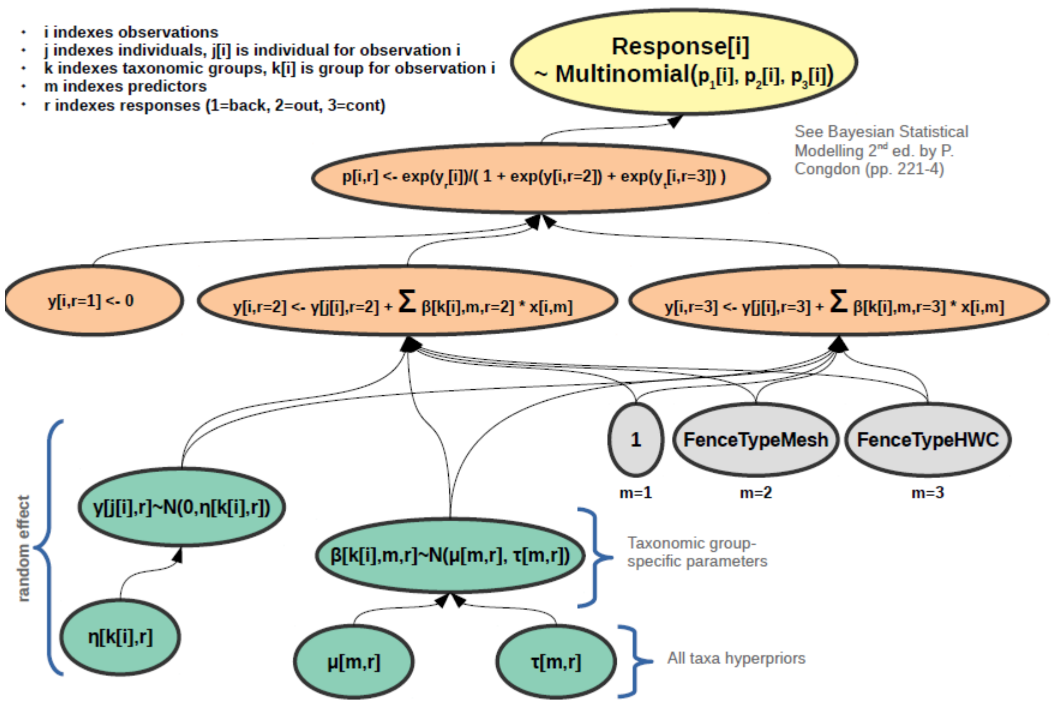


Figure 3. Turn Around Study: Multinomial Logit Choice Model for Response to Turn Around Structure

Time Spent in Turnarounds: Linear Regression:

We modelled time spent in the turnarounds using linear regression fitted by least squares to determine if time differed across fence types and taxonomic group (lizards, snakes, toads, and small mammals)(Program R):

Time ~ FenceType* TaxonomicGroup

Results

We captured useable video of 790 individual turnaround encounters that met our distance criteria. This represented 264 lizard, 96 snake, 59 toad, one frog, and 370 small mammal movements (Table 1). Among all herpetofauna, 92% changed course back toward the fence line or back out into the habitat. A total of 64% of lizard, 68% of snake, 80% of toads and 43% of small mammal movements were made back along the original fence line after encountering a turnaround.

Table 1. Species Documented Using Turnarounds and Movement Trajectory Results

		Fence lines passed (out of 6)			Proportion
Taxon	Species	Continued	Out	Back	Back+ Out
Lizard	*SubTotal*	26	69	169	0.90
	Aspidoscelis hyperythrus	12	53	69	0.91
	Aspidoscelis tigris			2	1.00
	Elgaria multicarinata			1	1.00
	Plestiodon gilberti			1	1.00
	Plestiodon skiltonianus		1		1.00
	Sceloporus occidentalis	3	1	15	0.84
	Uta stansburiana	11	14	79	0.89
	Unknown lizard			2	1.00
Snake	*SubTotal*	1	30	65	0.99
	Coluber fuliginosus		2	12	1.00
	Coluber lateralis	1	9	23	0.97
	Coluber flagellum		6	9	1.00
	Crotalus oreganus		6	5	1.00
	Crotalus ruber		2	1	1.00
	Lampropeltis getula		2	3	1.00
	Pituophis catenifer		2	11	1.00
	Salvadora hexalepis		1		1.00
	Unknown snake			1	1.00
Toad/Frog	*SubTotal*	5	8	47	0.92
	Anaxyrus boreas	4	5	31	0.90
	Pseudacris regilla			1	1.00
	Unknown anuran	1	3	15	0.95
Small Mammal	*SubTotal*	120	91	159	0.68
	Chaetodipus spp.	3	15	33	0.94
	Dipodomys simulans	29	22	36	0.67
	Microtus californicus	3	2	2	0.57
	Neotoma spp.	5	2		0.29
	Notiosorex crawfordii	1	1	2	0.75
	Otospermophilus beecheyi	41	16	35	0.55
	Peromyscus spp.	37	30	47	0.68
	Reithrodontomys megalotis		1	1	1.00
	Thomomys bottae		2	1	1.00
	Unknown rodent	1		2	0.67
	Grand Total	152	198	440	0.81

Across fence types, results of the multinomial logit choice model showed high probabilities (ρ) that lizards, snakes, and toads changed their trajectory of movement (back, out) after encountering and exiting a turnaround (Lizard ρ= 0.88, 90% CI 0.70–1.00, Snakes ρ= 0.98, 90% CI 0.77–1.00, Toad ρ= 0.90, 90% CI 0.62–1.00). Responses by lizards and toads, but not snakes, varied by fence type (Figure 4). Lizards and toads were generally more likely to change their trajectory (back, out) after encountering mesh and hardware cloth turnarounds in comparison to solid turnarounds.

Mammals had an overall lower probability than herpetofauna of changing their trajectory after exiting turnarounds (back and out ρ= 0.59, 90% CI 0.41–0.84). By fence type, mammals were more likely to change their trajectory (back, out) after encountering hardware cloth turnarounds in comparison to solid and mesh turnarounds.

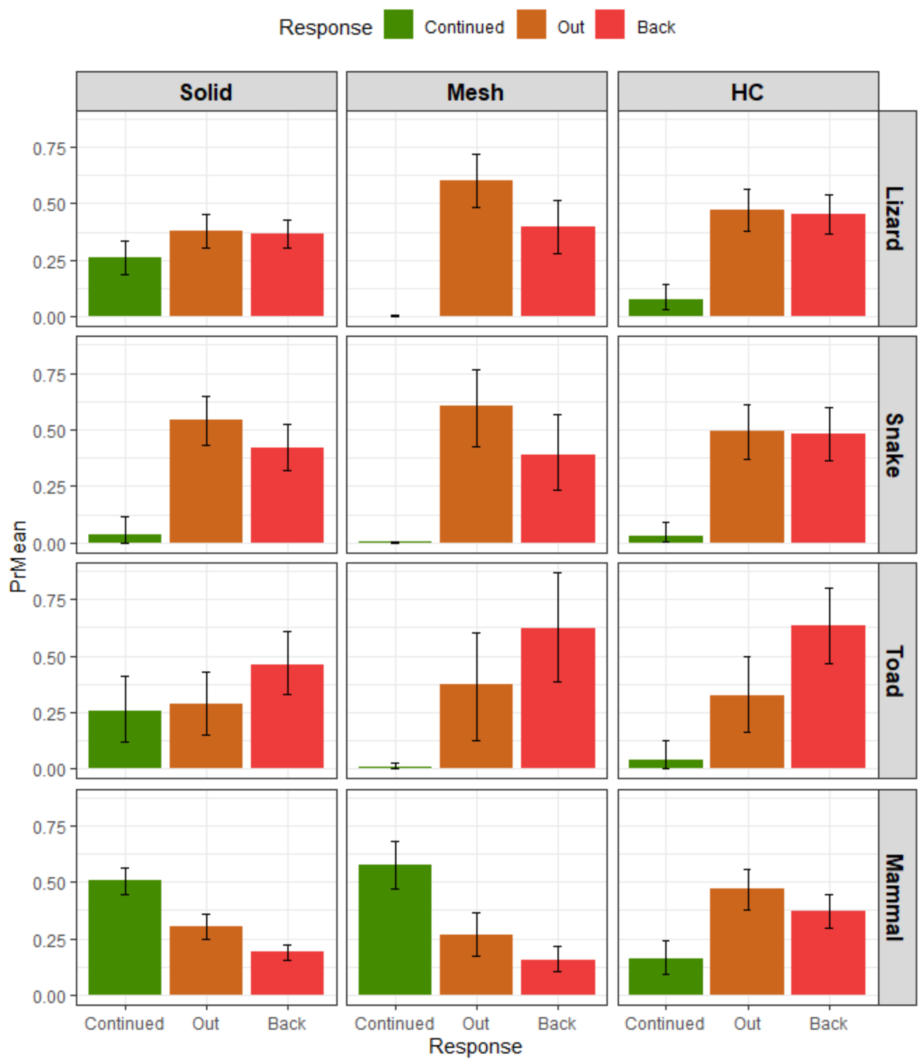


Figure 4. Directional Probabilities After Exiting Turnaround by Taxonomic Group and Fence Type (+/- 90% CI)

By Fence Type, all groups except toads spent significantly less time in the solid turnarounds than in the hardware cloth turnarounds ($p<0.001$; Table 2, Figure 5). Overall by taxon, mammals spent the least time in turnarounds (ave. model estim.=0.4 min), followed by snakes (ave. model estim=1.9 min), lizards (ave. model estim= 2.7 min), and toads (ave. model estim=3.0 min).

Table 2. Effects and Interactions of Fence Type and Taxon on Time spent in Turnaround

Coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept= Solid/Lizard)	*0.105*	*0.136*	*0.777*	*0.437*	
FenceTypeMesh	*1.083*	*0.286*	*3.788*	*1.65E-04*	***
FenceTypeHC	*1.240*	*0.218*	*5.683*	*1.96E-08*	***
TaxGroup1Mammal	*-1.424*	*0.177*	*-8.063*	*3.31E-15*	***
TaxGroup1Snake	*-0.009*	*0.275*	*-0.032*	*0.974*	
TaxGroup1Toad	*0.698*	*0.307*	*2.271*	*0.023*	*
FenceTypeMesh:TaxGroup1Mammal	*-0.926*	*0.371*	*-2.498*	*0.013*	*
FenceTypeHC:TaxGroup1Mammal	*-0.587*	*0.298*	*-1.971*	*0.049*	*
FenceTypeMesh:TaxGroup1Snake	*-0.699*	*0.560*	*-1.248*	*0.212*	
FenceTypeHC:TaxGroup1Snake	*-0.263*	*0.400*	*-0.658*	*0.511*	
FenceTypeMesh:TaxGroup1Toad	*-0.498*	*0.665*	*-0.748*	*0.454*	
FenceTypeHC:TaxGroup1Toad	*-1.030*	*0.500*	*-2.059*	*0.040*	*
(Intercept= Solid/Lizard)	*0.105*	*0.136*	*0.777*	*0.437*	

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

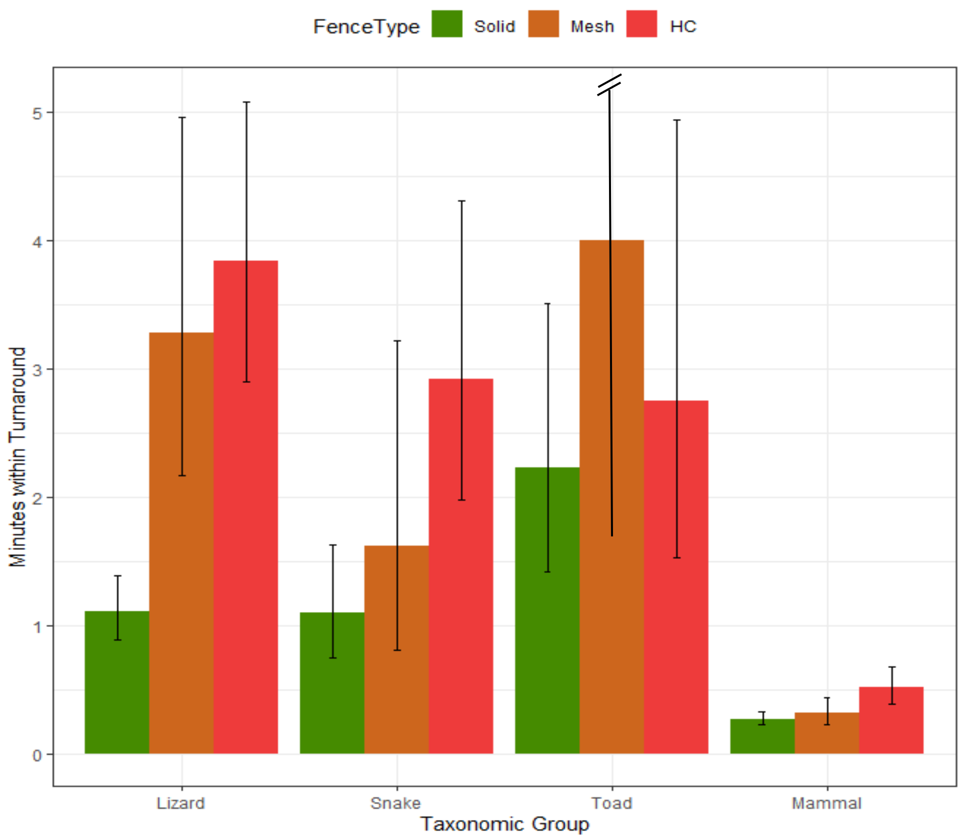


Figure 5. Estimated Time Spent in Turnaround by Taxonomic Group and Fence Type (+/- 90% CI)

Discussion

Our study is the first to show that small turnarounds at fence ends can be effective in changing the trajectory of movement for a majority of herpetofauna and small mammals. We documented that over 90% of herpetofauna (lizards, snakes and toads), as well as 69% of small mammals, changed course after leaving the turnaround. Of these 67% of herpetofauna and 43% of small mammals moved back along the original fence line. We (Chapter 5), and others (Ruby et al. 1994, Milburn-Rodríguez et al. 2016) have shown that animals spend more time interacting with fencing that they can see and smell through (e.g. poking, back and forth movements, climbing). We observed this in the turnaround study as well, as lizards, snakes and small mammals spent increased amounts of time in transparent/permeable and semi-transparent/permeable turnarounds than solid turnarounds.

Turnarounds made of solid fencing appeared to be less effective in changing the movement trajectory of lizards and toads in comparison to mesh and hardware cloth fencing. In addition, both solid and semi-transparent mesh fencing appeared to be less effective in changing the trajectory of small mammals in comparison to more transparent hardware cloth. These results could be related to animals interacting with the fencing and spending more time in the more transparent turnarounds, so that they were less likely to remember and continue on their original trajectory. The results may also be related to the different types of spatial learning and memory used for navigation when animals are subjected to solid barriers (egocentric) in comparison to transparent barriers (allocentric) as has been shown in maze-food trials with rodents (Violle et al. 2009, Vorhees and Williams 2014). Validation of these findings in other locations and possibly more specific research studies addressing spatial learning and movement responses in reptiles, amphibians, and small mammals in their natural environments would be needed to further our understanding of these results.

We did not compare different sizes or shapes of turnarounds in our study; however, we hypothesize that having the end of the turnaround close to the original fence line (or turning back in toward the fence line) may help to steer animals back to the original barrier in the other direction. We chose not to install large turnarounds as we wanted to reduce the probability of animals becoming stressed or 'trapped' in the turnarounds for long periods of time. However, longer turnarounds or larger turnarounds encompassing smaller turnarounds may increase the probability that animals do not make it onto the roadways (Langton and Clevenger 2021). Our study also suggests the use of transparent or semi-transparent fencing for turnarounds may potentially increase their effectiveness.

In this study, we only documented animal movement for up to 1 m (3.4 feet) after leaving the turnaround. It is entirely possible that animals changed course again after they left the field of view of the video camera. In our Stanford and Sierra movement studies (Chapters 3 and 4), two out of three CTS that presumably reached a turnaround at the fence end were subsequently documented on another camera 25-125 m away moving back along the fence line. Preliminary results suggest seven out of 10 Yosemite toads changed course at a turnaround, while three continued in the direction past the fence ends. Of the seven toads that changed course, four were subsequently documented on another camera 40-80 m away moving back along the fence line toward the passage. Further studies using more cameras and/or tracking methods are needed to better understand how turnarounds affect movement of animals over a longer distances and time frames. Higher mortality of herpetofauna has been well documented at fence ends even with turnarounds (Gunson et al. 2014, Langton and Clevenger 2017, Helldin and Petrovan 2019). However, the high proportion of herpetofauna that changed directions in our study supports the use of turnarounds in attempts to reduce the chances that small animals go out onto the roadway at fence ends and potentially to help 'steer' them back toward to a crossing structure.

In our migrating California tiger salamander (Chapter 4) and Yosemite toad studies (Chapter 5), we also found that these amphibian species were much less likely to encounter a crossing structure if they started out in the 'wrong' direction (i.e. moving away from the crossing after encountering a barrier). Many animals "gave up" before reaching the fence ends. These results suggest that more regularly placed turnarounds along the fence lines may allow them to correct their trajectory sooner and possibly increase their chances of making it to crossing structures. If effective, this strategy may help to increase the permeability of crossing structures to individual and population movements of reptiles and amphibians (and small mammals). These studies are currently in the planning stages.

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References

Clevenger, AP and MP Huijser. 2011. Wildlife Crossing Structure Handbook, Design and Evaluation in North America, Publication No. FHWA-CFL/TD-11-003. Department of Transportation, Federal Highway Administration, Washington D.C., USA.

Gunson, KE, DC Seburn and D. Lesbarrères. 2014. Monitoring turtle movements on Highways 7 & 41; 2012 and 2013. Final report submitted to the Ministry of Transportation, Kingston, Ontario.

Gunson, K, D Seburn, J Kintsch and J Crowley. 2016. Best Management Practices for Mitigating the Effects of Roads on Amphibian and Reptile Species at Risk in Ontario. Ontario Ministry of Natural Resources and Forestry. Queen's Printer for Ontario. 112 pp.

Helldin, JO and SO Petrovan. 2019. Effectiveness of small road tunnels and fences in reducing amphibian roadkill and barrier effects at retrofitted roads in Sweden. PeerJ, 7, p.e7518.

Iuell, B., GJ Bekker, R Cuperus, J Dufek, G Fry, C Hicks, V Hlaváč, V.Keller, B Rosell, T Sangwine and N Třrslřv. 2003. COST 341–Wildlife and traffic: a European handbook for identifying conflicts and designing solutions. URL: *https://www. milieuinfo. be/productie/beheerplone/nietacm/iene/cost-341/COST*.

Langton, TES and AP Clevenger. 2017. Amphibian and Reptile Highway Crossings: State of the practice, gap analysis and decision support tool. Report prepared for the State of California, Department of Transportation, Division of Research, Innovation and System Information, Office of Materials and Infrastructure Research, June 2017

Langton, TES and AP Clevenger. 2021. Measures to Reduce Road Impacts on Amphibians and Reptiles in California. Best Management Practices and Technical Guidance. Prepared by Western Transportation Institute for California Department of Transportation, Division of Research, Innovation and System Information.

Milburn-Rodríguez JC, J Hathaway, K Gunson, D Moffat, S Béga and D Swensson. 2016. Road mortality mitigation: The effectiveness of Animex fencing versus mesh fencing. *https://animexfencing.com/whyanimex/animex-vs-mesh*.

Ontario Ministry of Natural Resources and Forestry. April 2016. Best Management Practices for Mitigating the Effects of Roads on Amphibians and Reptile Species at Risk in Ontario. Queen's Printer for Ontario. 112 pp.

Ruby, DE, JR Spotila, SK Martin and SJ Kemp. 1994. Behavioral responses to barriers by desert tortoises: implications for wildlife management. Herpetological Monographs 8: 144–160.

Vorhees, CV and MT Williams. 2014. Assessing spatial learning and memory in rodents. ILAR Journal 55(2): 310–332.

Violle, N, F Balandras,Y Le Roux, D Desor. and H Schroeder. 2009. Variations in illumination, closed wall transparency and/or extramaze space influence both baseline anxiety and response to diazepam in the rat elevated plus-maze. Behavioural Brain Research 203(1): 35–42.