National Center for Sustainable Transportation
A USDOT University Transportation Center

Research Report

April 2025

Wildlife Connectivity and Which Median Barrier Designs Provide the Most Effective Permeability for Wildlife Crossings

Lorna Haworth, Benjamin Hodgson, Leo Hecht, Michelle See, Ash Henderson, Shannon Lemieux, Laura Morris, David Waetjen, and Fraser Shilling

University of California, Davis

ITS UCDAVIS
Institute of Transportation Studies

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. NCST-UCD-RR-25-11	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Wildlife Connectivity and Which Median Barrier Designs Provide the Most Effective Permeability for Wildlife Crossings		**5. Report Date** April 2025 **6. Performing Organization Code** N/A
7. Author(s) Lorna Haworth, https://orcid.org/0009-0009-9405-5582 Benjamin Hodgson, https://orcid.org/0009-0003-7580-5866 Leo Hecht, https://orcid.org/0009-0008-5444-5239 Michelle See, https://orcid.org/0009-0004-9444-3239 Ash Henderson, https://orcid.org/0009-0001-9625-1896 Shannon Lemieux, https://orcid.org/0009-0000-2943-1283 Laura Morris, https://orcid.org/0009-0003-4042-5847 David Waetjen, Ph.D., https://orcid.org/0000-0001-5817-3279 Fraser Shilling, Ph.D., https://orcid.org/0000-0001-8125-2186		**8. Performing Organization Report No.** UCD-ITS-RR-25-06
9. Performing Organization Name and Address University of California, Davis Institute of Transportation Studies 1605 Tilia Street, Suite 100 Davis, CA 95616		**10. Work Unit No.** N/A **11. Contract or Grant No.** Caltrans 65A0686 Task Order 085 USDOT Grant 69A3552348319 and 69A3552344814
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE, Washington, DC 20590 California Department of Transportation Division of Research, Innovation and System Information, MS-83 1727 30th Street, Sacramento, CA 95816		**13. Type of Report and Period Covered** Final Research Report (April 2024 – December 2024) **14. Sponsoring Agency Code** USDOT OST-R Caltrans DRISI
15. Supplementary Notes DOI: https://doi.org/10.7922/G2BV7DZ6 Data from this project can be accessed at https://roadecology.ucdavis.edu/research/projects/median-barriers.		
16. Abstract Median barriers are usually constructed to reduce head-on-crashes between vehicles on undivided highways. Because of their position in the center of the traveled right-of-way, median barriers could affect wildlife movement across the right-of-way, decreasing wildlife connectivity. The authors coordinated and met with staff from several Caltrans Districts to gain understanding of their issues related to median barriers and wildlife permeability. The authors used previously and newly collected wildlife-vehicle collision (WVC) observations to test whether or not median types have different effects on unsuccessful wildlife crossings of the road surface. The authors used Generalized Linear Models (GLM) to compare WVC rates among median treatment types in three Caltrans Districts (2, 4, 9) for four wildlife species. The primary findings were that there are effects of median types on rates of WVC and that these effects varied by species and to some degree by geographic region (represented by Caltrans District). The primary finding is that fewer wildlife enter roadways and are killed in the presence of constructed median types than other types. Although this may result in a reduction in WVC, it also results in a reduction in wildlife permeability as most roadways do not have crossing structures and therefore attempts at wildlife permeability will be across the road surface.		
17. Key Words Median barrier, wildlife connectivity, wildlife-vehicle collision		**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 41	**22. Price** N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

About the National Center for Sustainable Transportation

The National Center for Sustainable Transportation is a consortium of leading universities committed to advancing an environmentally sustainable transportation system through cutting-edge research, direct policy engagement, and education of our future leaders. Consortium members include: the University of California, Davis; California State University, Long Beach; Georgia Institute of Technology; Texas Southern University; the University of California, Riverside; the University of Southern California; and the University of Vermont. More information can be found at: ncst.ucdavis.edu.

Disclaimer

Acknowledgments

This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST), supported by the U.S. Department of Transportation (USDOT) and the California Department of Transportation (Caltrans) through the University Transportation Centers program. The authors would like to thank the NCST, the USDOT, and Caltrans for their support of university-based research in transportation, and especially for the funding provided in support of this project.

Wildlife Connectivity and Which Median Barrier Designs Provide the Most Effective Permeability for Wildlife Crossings

A National Center for Sustainable Transportation Research Report

Lorna Haworth, Benjamin Hodgson, Leo Hecht, Michelle See, Ash Henderson, Shannon Lemieux, Laura Morris, David Waetjen, and Fraser Shilling

Road Ecology Center, University of California, Davis

Table of Contents

List of Tables

List of Figures

Wildlife Connectivity and Which Median Barrier Designs Provide the Most Effective Permeability for Wildlife Crossings

Executive Summary

Median barriers are usually constructed to reduce head-on-crashes between vehicles on undivided highways and the type (e.g., cable, metal beam guardrail, concrete) is based on state requirements for crash mitigation. Because of their position in the center of the traveled right-of-way, median barriers could affect wildlife movement across the right-of-way, decreasing wildlife connectivity. There are several types of center-median and right-of-way edge barriers, with cable barriers possibly providing the most wildlife permeability and concrete Jersey barriers the least.

There is still little understanding of: 1) the positive or negative relationship between medians of various types and wildlife-vehicle collision (WVC, type and rate), or connectivity; 2) the influence of other variables in the potential relationships in (1), such as traffic volume and adjacent habitat; 3) the effect of median types on successful wildlife movement/connectivity (i.e., non-WVC); and 4) the effect of mitigation of the barrier effect of median barriers, such as change in type, or creation of gaps. We coordinated and met with staff from several Caltrans Districts early in the project to gain understanding of their issues related to median types and wildlife permeability. All staff with whom we initially communicated will receive a copy of this report.

We used previously collected and newly collected WVC observations to test whether or not median types have different effects on unsuccessful wildlife crossings of the road surface. Our null hypothesis was that there was no effect of median type on WVC rates. We also tested two alternative hypotheses: H1) Certain median types correlate with changes in WVC rates across species. A corollary is that median types can affect wildlife permeability in general; and H2) Certain median types correlate with changes in WVC rates for individual species. A corollary is that median types can affect permeability for individual species or species types. We used Generalized Linear Models (GLM) to compare WVC rates among median types in 3 Caltrans Districts (2, 4, 9) for four wildlife species: Western gray squirrel (*Sciurus griseus*), Black-tailed jackrabbit (*Lepus californicus*), Coyote (*Canis latrans*), and Mule deer (*Odocoileus hemionus*). Our primary findings were that there are effects of median types on rates of WVC and that these effects varied by species and to a lesser degree by geographic region (represented by Caltrans District). For example, mule deer and Western gray squirrel WVC rates were affected similarly by median type across Districts, whereas coyote WVC rate was affected differently from deer and squirrel. We disproved the null hypothesis, that there was no effect of median type on WVC rates and suggest that the best alternative hypothesis is H2, that there is an effect of

median type on WVC rates and it varies by species and potentially animal size. There are several possible explanations for our results, leading to new hypotheses: 1) Animals have varying behavior when looking across the road surface toward different median types; 2) Once reaching the center median, animals respond differently to each median type. We discuss these in more detail in the report. The primary finding is that fewer wildlife enter roadways and are killed in the presence of constructed median types than undeveloped types. Although this may result in a reduction in WVC, it also results in a reduction in wildlife permeability.

Introduction

Habitat Fragmentation and Wildlife Connectivity

Habitat fragmentation and loss due to transportation infrastructure and land use change are some of the greatest threats to biodiversity (Wilcove et al. 1998; Fahrig 2003; Tscharntke et al. 2012). Landscape connectivity, defined as the degree to which the landscape facilitates or impedes movement among resource patches (Taylor et al. 1993), has emerged as a key component of biological conservation. Constructing methods for wildlife to move over or under highways can mitigate road-mediated habitat fragmentation, by facilitating safe wildlife passage and reducing the risk of wildlife-vehicle collisions (WVC). However, structure use can vary with taxonomic group and the characteristics of the structure (Kintsch and Cramer 2011). Road-surface crossing may be a common method for many species to maintain connectivity, but it comes with risks from traffic.

Wildlife movement and behavior in response to traffic and roads and related infrastructure, such as culverts, bridges, median vegetation and barriers, can vary widely among taxonomic groups. Small animals (herpetofauna and small mammals) may move in straight lines (Matthews and Pope 1999, Sinsch 2006, Southwood and Avens 2010), including along the road verge (Gunson et al. 2011). Small animal mortality on roads may be distributed evenly along roads adjacent to suitable habitat (Glista at al. 2007, Matos et al. 2012), in other words, not concentrated in “hotspots”. Murid species, such as deer mice, respond to roads differently from each other, potentially because species have different habitat preference and tolerance for open spaces (McDonald and St. Clair 2004). Similarly, small and medium-sized mammals respond differently to different opening types (e.g., pipe culvert), which could affect their use (Martinig and Bellanger-Smith 2016). Constructed crossing structures for small animals have been demonstrated to be effective using camera traps (e.g., Foresman 2004), camera traps and roadkill surveys (e.g., Snyder 2014), and a combination of camera traps, roadkill surveys, and animal sign observation (e.g., Ortega et al. 2021). All of this means that species are likely to respond differently to the same traffic and infrastructure.

WVC can affect wildlife populations and can be a barrier to permeability across roads for small animals (e.g., Brehme et al. 2013), as traffic is essentially a moving wall preventing animals from crossing a road. Small mammals and herpetofauna (amphibians and reptiles) can have very high rates of mortality on roads. For example, Smith and Dodd (2003) found 1,821 carcasses of 62 species of small animals on a 3.2-kilometer section of a Florida highway 1 year prior to wildlife passage/barrier wall construction. An investigation of effectiveness of the construction by the same team (Dodd et al. 2004) found a 65% reduction in the number of carcasses in the mitigation area, with most of these located around the ends of barriers and at access-road openings onto the highway. Small mammals and herpetofauna accounted for most of the mortality, possibly due to climbing the barrier wall and going around the ends of the barriers.

Medians and Median Barriers

Median describes the middle of a two-way road alignment, where there is typically [illegible] combination of these (Figure 1). Each of these median types will have different consequences for different wildlife species and groups, meaning that there will be many possible combinations of median and species. Median barriers are typically deployed to prevent head-on collisions using concrete barriers (e.g., K-rail/Jersey barriers), cable barriers, or metal beam guardrail. Developed (e.g., paved) or undeveloped (vegetated) median areas are typically wide enough to prevent head-on collisions and may include large areas of habitat for certain species.

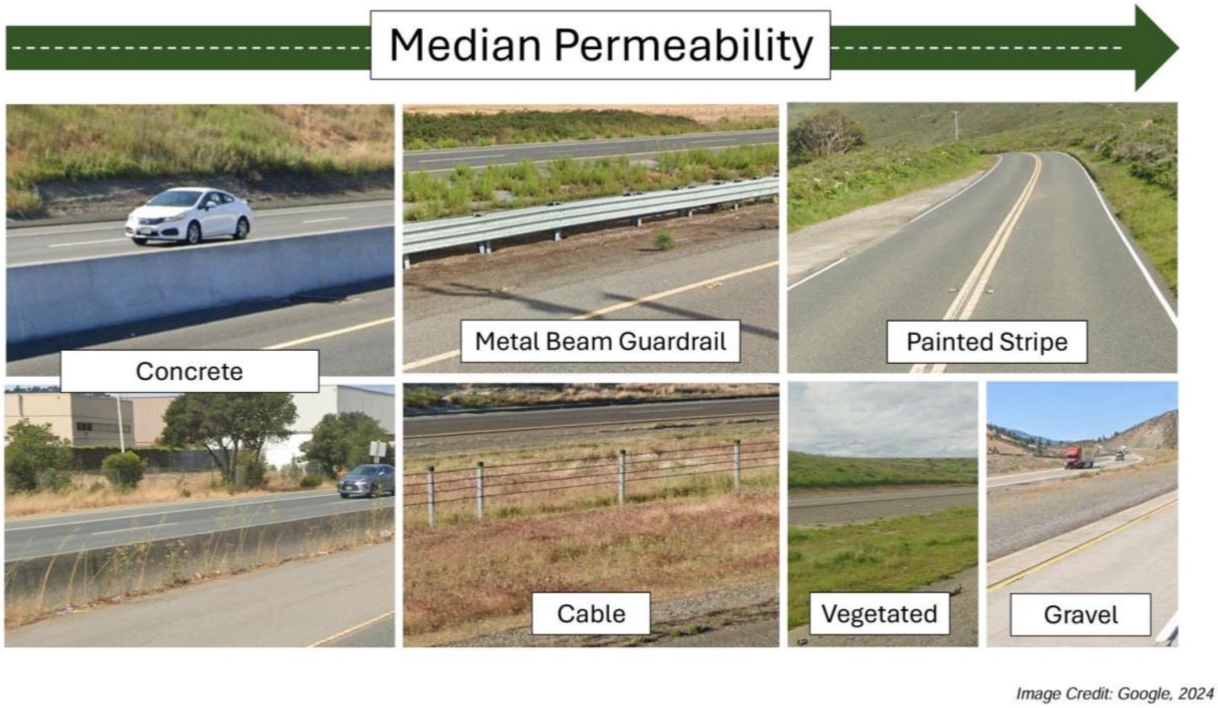

Figure 1. Median types and possible permeability to wildlife movement.

The following sections summarize the literature available to describe median conditions and how they can affect wildlife movement.

Vegetated Medians

Vegetated medians may initially seem like places wildlife could use for foraging or travel, reducing the barrier effects of roads. However, McLaren et al (2011) found that small mammals were hesitant to cross highways and the presence, or width of vegetation in the median did not reduce this effect. In addition, there was not an apparent relationship of the hesitancy with traffic volume, but there was species dependence. In contrast, McDonald and St Clair (2004) found that vegetated medians were less of a barrier to small mammal movement than the highway itself, possibly reducing the effect of the highway. When median areas are accessible from wildlife crossing structures, small mammals will access and forage in these areas, which could limit passage through the structures to the other side of the highway (Martinig and Belanger-Smith, 2016). Martinig and McLaren (2019) found that five mammal species or species groups would leave culverts (<5 feet in height) within the median and forage. Rates of deer and elk mortality on a highway were reported to be higher in the vicinity of vegetated medians (Singleton and Lehmkuhi, 2000). This increase in wildlife mortality with roadside and median vegetation seems to be a general phenomenon (reviewed in Riley et al., 2014).

In general, vegetated medians may provide foraging opportunities, but this will be amidst traffic. If access to the vegetated medians is provided from crossing structures, this may limit effective passage of wildlife from one side of the roadway to the other, defeating the primary purpose of the structure. The only benefit of median vegetation appears to be as a stepping stone across a right-of-way, however, attraction of wildlife to the middle of a divided highway may result in higher rates of roadkill than would otherwise occur.

Median Barriers

There are several types of median barriers, with cable barriers providing the most wildlife visibility and possibly permeability and concrete Jersey barriers the least. Deploying median barriers is often based on human safety concerns and the type (e.g., cable vs. Jersey) based on state requirements for crash mitigation.

Traffic Safety

Median barriers can both increase the frequency of vehicle crashes, and both reduce and increase severity of crashes (reviewed in Hu and Donnell, 2010). Concrete and three-beam barriers contribute to greater severity of vehicle crashes than cable barriers (Russo and Savolainen, 2018). Cable barriers, especially those with greater lateral deflection, can absorb more force without redirecting a vehicle back into traffic lanes (Russo and Savolainen, 2018).

Wildlife Impacts

Awareness of the potential impact of median barriers on wildlife movement began at the turn of the century, with three key technical and scientific studies. Cooper (1999) described possible barrier effects of median barrier placement for smaller wildlife attempting to move across the trans-Canada highway. Focusing more on larger animals, Singleton and Lehmkuhi (2000) found that rates of deer and elk roadkill were lower in the vicinity of roadside Jersey barriers. In a possible explanation for this, deer, elk and coyotes were reported to be hesitant to jump over Jersey or guardrail types of roadside barriers to enter roadways, but would jump them to escape a roadway (Barnum, 2003). Similarly, Malo et al. (2004) found a negative relationship between presence of a median barrier and roadkill incidents and Dodd et al. (2004) found that barriers built on the side of a highway to prevent herpetofauna mortality, were >70% effective at reducing herpetofauna roadkill. Finally, and similar to previous studies, Gunson et al. (2011) found that there was a negative relationship between distance to barrier, or length of barrier and rate of large mammal collisions. Findings from these and other studies were later summarized in a review by Clevenger and Kociolek (2013). They identified several studies that found mammal roadkill rates were higher in the presence of concrete barriers, but concluded that there was no correlation between presence of a median barrier and rates of roadkill. They also suggested that the lack of consistency could be related to poor recognition of confounding factors in statistical analysis. Snyder (2014) found a negative relationship between roadkill rates and median barrier type and distance to gaps in median barriers. Kim et al (2021) found a negative relationship between presence of median barriers and concentrations of roadkill. Pagany and Dorner (2019) also found a significant negative relationship between the presence of median barriers and roadkill, in particular for smaller animals. For bobcats specifically, Serieys et al. (2021) found that the lowest rate of attempted road-surface crossing and most mortalities occurred in association with high median barriers.

These results strongly suggest that concrete median barriers inhibit wildlife attempting to cross roads, but where wildlife do, they may become trapped, concentrated at breaks in the barrier, or concentrated at the end of the barrier. In general, roadkill rates would be expected to be lower in the presence of concrete median barriers. Although median barrier height was rarely included as a variable in these studies, if reduced roadkill is due to wildlife perception of a wall, then the relative height of the wildlife and the barrier will be important. Results from Snyder (2014) and others suggest that visible breaks in median barriers may provide wildlife with a visual cue to attempt to cross the road surface. Whether it is safe to do so from a traffic volume point of view is a separate question.

Hypotheses/Questions

Wildlife permeability across roadways with various median types was the focus of this study. Roadkill/wildlife-vehicle collision (WVC) rates were used as a proxy for wildlife permeability, with important qualifiers. The following are the hypotheses and questions we addressed, followed by caveats.

Null Hypothesis (Ho): There is no effect of median type on WVC rates. A corollary is that there is no effect of median type on wildlife permeability.

Alternative Hypothesis 1 (H1): Certain median types correlate with changes in WVC rates across species. A corollary is that median types can affect wildlife permeability in general.

Alternative Hypothesis 2 (H2): Certain median types correlate with changes in WVC rates for individual species. A corollary is that median types can affect permeability for individual species or species types.

Caveats: 1) WVC rates indicate both that wildlife attempted to cross a road and failed to do so. Increased WVC rates can indicate both that more wildlife attempted to cross and that more failed. Decreased rates indicate the converse. However, increased WVC rates can occur with no increase in attempts to cross, but an increased failure rates for those that do. 2) Wildlife behavior is only generally represented by WVC and may be the primary determinant of wildlife permeability through the median. This behavior is multi-faceted, including wildlife decisions in four important phases of crossing the right-of-way (ROW): a) approaching the roadway, which can be impacted by perception of traffic noise and light and surrounding habitat cover and topography; b) at the roadside, where traffic disturbance is near its greatest, the width or openness of the road is apparent, and the median is visible; c) on the road surface, where traffic, road width, and median conditions are all at play; and d) at the median, itself, where the ability to actually cross the median (e.g., Jersey barriers) and immediately adjacent traffic may all affect behavior.

Methods

The following sections describe the study areas, datasets, data collection methods, and statistical analysis methods.

Study areas

Two primary scales of study areas were used: 1) Local: paired median types. These are pairs of 1-5-mile-long stretches of state highway or interstate with different median types in each half of the pair (Figure 2). For example, 1 mile of concrete median barrier adjacent to 1 mile of vegetated median. 2) Districts 2, 4, and 9 median types at WVC points. Median types were determined where WVC points were identified.

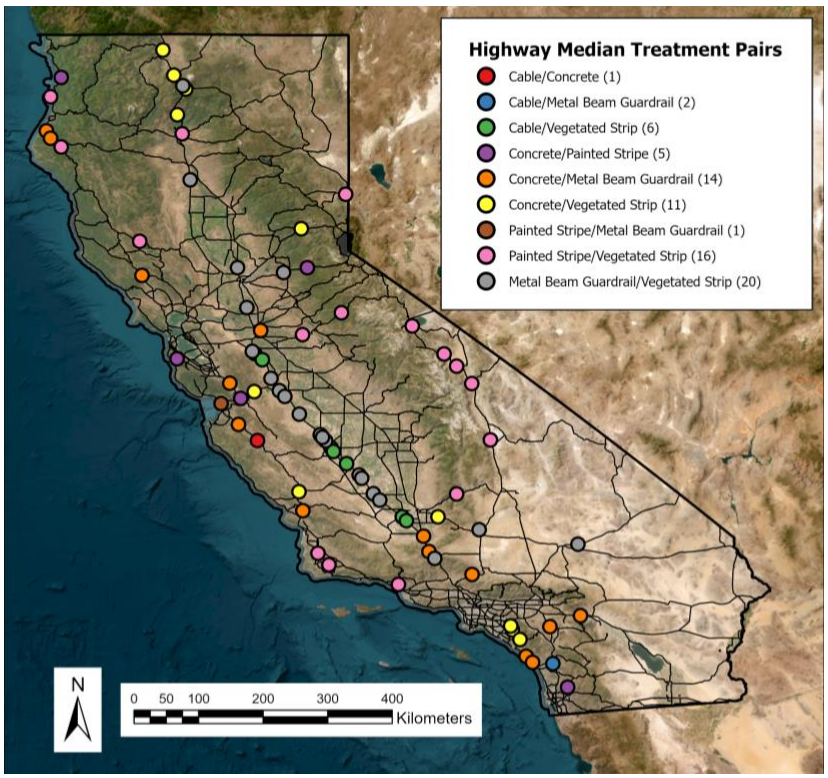

Figure 2. Locations of paired median types.

Caltrans Coordination

We coordinated with Caltrans District staff by email and in a meeting on August 26, 2024. Caltrans staff were interested in several main themes during our discussions: 1) were there recent median barrier installations that we could study from a before-after perspective; 2) what impacts did barriers have on individual species of concern (e.g., Mojave ground squirrel in District 9); 3) could we differentiate between median type and traffic effects, for example by comparing effects at different traffic levels; 4) are scuppers and concrete barrier breaks useful; 5) can behavior at median barriers be assessed with trail cameras; 6) if crossings are already present, do median barriers matter in terms of permeability impacts; and 7) how might differences in vegetation composition and density in vegetated medians cause or offset problems? We are planning on a final meeting with them after finalization of this report as a courtesy, to share our findings.

Data collection

Two primary types of data were used: WVC observations from previous and newly collected efforts and newly-collected infrastructure and composition information for adjacent habitats, roadside and roadway conditions.

Highway infrastructure

Adjacent habitats

Information for adjacent habitats to WVC observations was derived from the highest resolution land cover spatial datasets from the 2021 National Land Cover Database. The distance from each observation to the nearest 30 x 30 square meter area of each land cover class was calculated using a QGIS tool. Distance measurements were calculated for the following land cover classes: Open Water, Developed, Barren, Forest, Shrubland, Herbaceous, Planted/Cultivated, and Wetlands.

A potential limitation of these land cover datasets is their inability to capture small landscape features that may act impact animal movement. For example, a small pond may provide a drinking point for wildlife but would not be identified as a unique feature in the land cover dataset.

Paired median types (Local)

Local stretches of pairs of median types were manually identified using satellite, aerial, and ground-level imagery accessed through Google Earth Pro and Street View. Satellite/aerial imagery of state highways and interstates was systematically reviewed using Google Earth Pro to pinpoint changes in median type. Median type was then confirmed using ground-level imagery. For each identified change, 1- to 5-mile transects of continuous median type on either side of the change point were recorded. Median types included: concrete barrier, cable barrier, metal beam barrier, vegetated strip, and painted stripe. Pairs of transects were discarded if the land cover was visually dissimilar between the two transects or if multiple treatments were present. Valid transect pairs were converted into a spatial dataset of paired highway segments containing median treatment data using GIS software.

A 50-meter buffer was applied to the paired highway segments using GIS software to capture surrounding areas, and WVC observations located within the buffer zone were extracted to create a dataset of collisions occurring within the identified segments. The 50-

meter buffer width was chosen to account for animal carcasses found on highway road shoulders and within wide median strips. GIS software was then used to assign the median type, pair type (e.g., concrete barrier-vegetated strip pair), and unique pair identifier of the nearest highway segment to each collision. These data were then summarized to create a dataset containing WVC counts for both segments within each pair.

District-wide median types

Median type data for WVC observations in each District were manually collected using satellite, aerial, and ground-level imagery accessed through Google Earth and Google Earth Street View. The WVC point spatial datasets were imported into Google Earth Pro, and the median treatment for each WVC point was documented from the available overhead and ground-level imagery based on a predefined list of barrier and non-barrier treatments. Barrier treatments included: concrete, cable, and metal beam guardrails. Non-barrier treatments were unprotected strips that separate lanes and included: vegetated strips, gravel strips, and painted strips. When multiple treatments were present (e.g., a vegetated strip containing a metal beam guardrail), each treatment was recorded.

Existing wildlife-vehicle collision occurrences

WVC data were harvested from the Road Ecology Center's statewide datasets of crash and carcass occurrences. Crash data were from the California Highway Incident Processing System (CHIPS). These data are collected through an automated scraping and text-query process. The data are manually checked for type of animal, type of crash, and duplication. Carcass data were from both CHIPS and the California Roadkill Observation System (CROS, https://wildlifecrossing.net/california). CROS data are collected from individual observers, agency/organizational observers, and targeted collections (i.e., for certain roadways) and are manually reviewed for species and locational accuracy.

These data were divided into subsets for each study area based on specific filter criteria. For each study area, WVC observations occurring before 2015 were excluded to minimize the likelihood of median changes between the collision date and the imagery date.

Paired Medians Study

At the paired medians (local) scale, WVC observations were included if they were located within 50 meters of a valid transect pair. WVC observations of all species were included between January 2015 and April 2024.

We identified nine types of paired local median treatments across the state. Within the 76 pairs (152 individual transects), 1,181 wildlife-vehicle collisions occurred over 210.2 miles of total transect distance. Table 1 summarizes the data for each pair type.

Table 1. Summary of Local Median Type Pairs

Pair Type	Number of Pairs	Median Type	Number of WVCs	Total Distance (mi)
Cable / Concrete	1	Cable	1	1.0
		Concrete	1	0.99
Cable / Metal Beam Guardrail	2	Cable	16	2.04
		Metal Beam Guardrail	7	2.00
Cable / Vegetated Strip	6	Cable	23	10.08
		Vegetated Strip	30	10.13
Concrete / Painted Stripe	5	Concrete	74	5.00
		Painted Stripe	46	5.10
Concrete / Metal Beam Guardrail	14	Concrete	58	18.48
		Metal Beam Guardrail	90	17.89
Concrete / Vegetated Strip	11	Concrete	65	11.17
		Vegetated Strip	116	11.25
Painted Stripe / Metal Beam Guardrail	1	Painted Stripe	1	1.00
		Metal Beam Guardrail	9	1.01
Painted Stripe / Vegetated Strip	16	Painted Stripe	235	28.19
		Vegetated Strip	198	28.37
Metal Beam Guardrail / Vegetated Strip	20	Metal Beam Guardrail	87	28.07
		Vegetated Strip	124	28.41

District Study

Individual species WVC observation datasets were created for each of District 2, 4, and 9 (Figure 2). Observations in each study district were included if they were located within 50 meters from a highway centerline, they were on highway infrastructure accessible to wildlife, and if the median treatment could be determined from the available imagery.

Figure 2. Mule deer WVC data in each Caltrans District

For each District, a small-, medium-, and large-sized mammal species was selected for study based on the largest available observation dataset. In District 2 and District 4, the selected species were Western gray squirrel (*Sciurus griseus*), Coyote (*Canis latrans*), and Mule deer (*Odocoileus hemionus*). In District 9, the selected species were Black-tailed jackrabbit (*Lepus californicus*), Coyote, and Mule deer.

For each District, GIS software was used to create a corresponding set of randomly generated points along highways to serve as a comparison dataset. Some of these comparison points were located near the WVC observations. To address potential spatial autocorrelation, an additional comparison dataset was created using GIS software to include only the random points that were located more than 100 meters from the WVC observations.

Wildlife-vehicle collisions of several species were not distributed uniformly across the entire district and exhibited spatial clustering. We propose two explanations for this clustering:

1. Even reporting effort: Clustering reflects “hotspot” areas with collision rates
2. Uneven reporting effort: Clustering reflects areas with higher WVC reporting rates

Based on the first explanation that clustering reflects true WVC hotspots, a districtwide dataset including all WVC observation and comparison data was created (“All” in Table 4). Based on the second explanation that clustering reflects areas with higher WVC reporting rates, WVC observation and comparison data were clipped to the boundaries of Minimum Convex Polygons (MCPs) generated for major clusters (“Group” in Table 4). Major clusters were regions with assumed even reporting effort, measured by regular WVC observations, and did not include WVCs that were geographically isolated from the rest of the cluster.

This process resulted in two types of spatial datasets for each species in Districts 2, 4, and 9: districtwide (“All” in Table 1) and MCP (“Group” in Table 1) datasets. These datasets included various categories of points for analysis:

- Observations: All WVC points on highways for the species within each district.
- All random points: Randomly generated comparison points along the same highways as WVC observations, which serve as a baseline for spatial comparison.
- Random points greater than 100m from WVC: A subset of the randomly generated points located more than 100 meters from any WVC observation to produce pseudoabsences.

Table 2. Summary of Wildlife-Vehicle Collisions in Caltrans Districts

District	Mule Deer	Coyote	Western Gray Squirrel	Black-tailed Jackrabbit	Total Highway Distance (mi)
2	1407	73	333	0	2084.468
4	1131	321	82	0	2299.440
9	273	78	0	21	1399.480

Random points were generated at a 1:1 ratio to match the number of roadkill points except for District 4 Mule deer, where the random points totaled to 1095. Total datasets (roadkill and random points) by species were N=5,586 for mule deer, N=944 for coyote, and N=872 for western gray squirrel and black-tailed jackrabbit.

Field-collected wildlife-vehicle collision occurrences

New WVC data were collected in targeted surveys along previously identified paired highways transects. These surveys were carried out in Caltrans Districts (3, 4, 7) where staff had previously expressed some interest in the project. Pairs of students surveyed routes for animal carcasses (one driving and one observing) at the speed limit on 1 to 4 occasions. Duplicate observations collected on different days in the same location were not used. Observations were recorded using transect-survey functions in CROS, which was also used to manage the data.

Table 3. Summary of Field Surveys of Select Local Median Type Pairs

Pair Type	Number of Pairs	Total Survey Effort (days)	Median Type	Number of Surveyed Carcasses	Total Distance (mi)
Cable / Metal Beam Guardrail	1	3	Cable	0	1.00
			Metal Beam Guardrail	1	1.07
Cable / Vegetated Strip	3	5	Cable	6	7.03
			Vegetated Strip	8	7.04
Concrete / Painted Stripe	1	4	Concrete	0	1.00
			Painted Stripe	4	1.00
Concrete / Metal Beam Guardrail	5	9	Concrete	1	4.99
			Metal Beam Guardrail	2	4.71
Concrete / Vegetated Strip	4	4	Concrete	2	4.00
			Vegetated Strip	3	4.03
Painted Stripe / Vegetated Strip	1	3	Painted Stripe	0	1.01
			Vegetated Strip	0	0.99
Metal Beam Guardrail / Vegetated Strip	5	15	Metal Beam Guardrail	19	9.23
			Vegetated Strip	22	8.97

Statistical analyses

Two primary types of statistical analyses were carried out: 1) pairwise comparisons of adjoining median treatment types; and 2) generalized linear modeling (GLM), a type of regression analysis.

Pairwise analyses

Median treatment data for the paired highway transects in the local study area were analyzed to determine whether significant differences in WVC rates existed between the treatments within each pair type. Pair types were composed of combinations of these individual median treatments: metal beam guardrail, vegetated strip, concrete barrier, painted stripe, and cable barrier. R scripts were used to calculate the WVC rate for each transect (# of collisions / transect length in kilometers). 1,181 WVC observations across 76 transect pairs were included in the analysis.

Comparisons were performed for the following median treatment pair types: cable/concrete, cable/metal beam guardrail, cable/vegetated strip, concrete/painted stripe, concrete/metal beam guardrail, concrete/vegetated strip, painted stripe/metal beam guardrail, painted stripe/vegetated strip, and metal beam guardrail/vegetated strip. Other potential pair types were not analyzed due to insufficient data.

A secondary analysis was conducted based on the possible wildlife permeability of each median treatment. Median treatments were categorized as permeable (vegetated strip, painted stripe), semi-permeable (metal beam guardrail, cable barrier) or impermeable (concrete barrier). Comparisons were performed for the following permeability-based pair types: impermeable/permeable, impermeable/semi-permeable, and permeable/semi-permeable. Other potential pair types were not analyzed due to insufficient data.

Paired T-test

A parametric paired T-test was used to determine whether differences in the mean collision rate between segments in each median treatment pair type were statistically significant ($p<0.05$).

Wilcoxon Signed-Rank Test

A non-parametric Wilcoxon signed-rank test was used to determine whether differences in the median collision rate between segments in each median treatment pair type were statistically significant ($p<0.05$).

Generalized linear models

To determine whether median treatment type was predictive of WVC rates at the District scale, generalized linear model (GLM) statistical analyses were performed in R version 4.1.2 using the MASS, emmeans, and multicomp packages (R Core Team, 2021). All GLM iterations used WVC body condition as the response variable, with “dead” and “injured” considered a hit and random points as non-hits. A GLM with median type as the fixed effect was used to determine which was the most significant predictor of a WVC for each dataset. A pairwise comparison of the model was done using the estimated marginal means to compare predicted responses of the model with median type as the only predictor. The differences between groups were adjusted using a Tukey method. All coefficients from model outputs were back transformed from a log scale. A type II analysis of variance (Anova) test was run for each model iteration to determine significant predictors. Tests for correlation among variables were not conducted, though that is being done after the end of this project. Measurements for annual average daily traffic (AADT) and distance to various land cover classifications from the National Land Cover Database (NLCD), streams from the National Hydrography Database (NHD), and nearest building were added to the GLM to determine if there were additional significant indicators of WVC. The following are included in the landcover data: open water, developed low-high intensity, barren, forest, shrub, herbaceous, planted/cultivated, wetlands.

Results

The following sections describe the results of the statistical analyses.

Pairwise comparison

Neither the paired T-test, nor the Wilcoxon signed-rank test detected significant differences ($p<0.05$) in mean collision rates for either the treatment comparisons or the permeability-based comparisons (Figure 3). This is visually apparent with comparisons such as the total number of collisions for "Painted Stripe vs Vegetated Strip" (to bar in Figure 3) and also true for all other comparison in Figure 3.

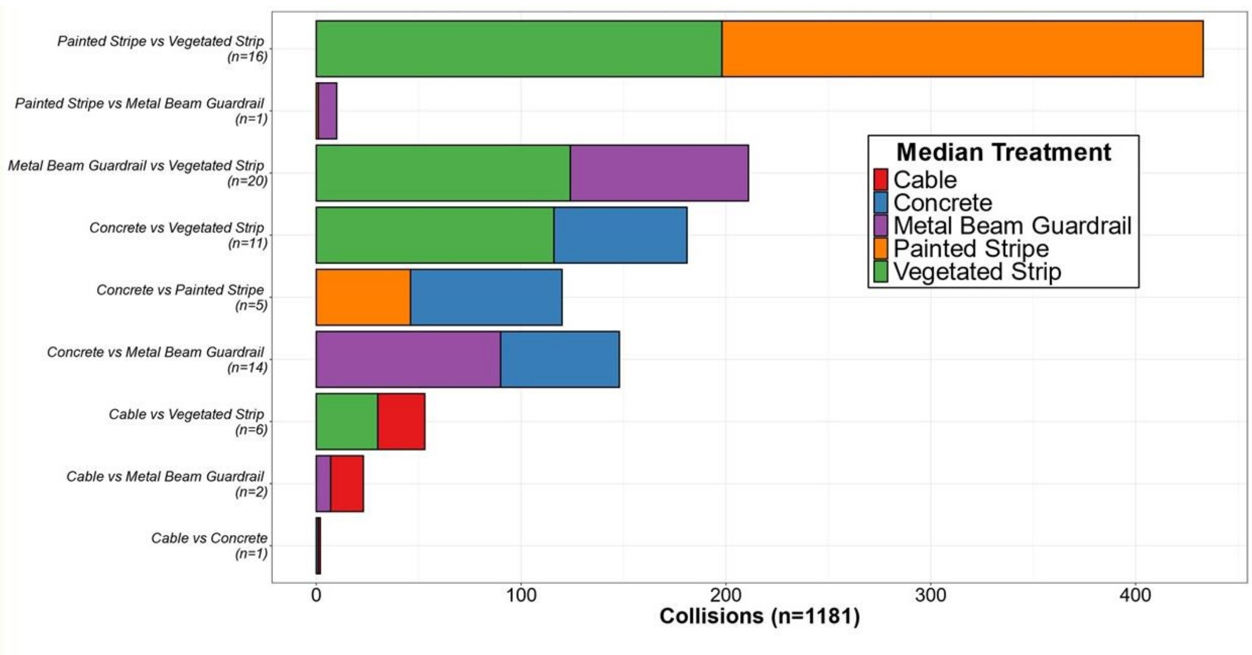

Figure 3. Wildlife-vehicle collision rates across paired median types transects.

Generalized linear modeling

Table 4 summarizes the results of the median type by species and Caltrans district with p-values from an Anova. P-values less than/equal to 0.05 are indicative of a significant effect of median treatment type on WVC. Impact indicates which median type has the strongest effect. Out of the 38 datasets, median type is a significant predictor of WVC 29 times (76%). For mule deer and coyote, WVC rates were most significantly related to painted stripe, vegetated strip, guard rail, and concrete barrier medians. Three of these four have some, or complete visibility through them, with only concrete barriers providing no visibility to the other side of the road. For western gray squirrel and black-tailed jackrabbit, WVC rates were only significantly correlated with painted stripe medians.

Table 4. Summary of median barrier (GLM) model results

Species Size	Species	District	Group	P-values[1]	Impact[1, 2]
Large	Mule Deer	2	All	0.0001778*	MG
		4	All	3.765e-08*	PS
		9	All	0.003885*	CB
			1	0.03377*	VS
Medium	Coyote	2	All	0.0005309*	VS
			1	8.512e-16*	MG
			2	0.00347*	MG
		4	All	0.0001016*	MG
			1	0.02496*	GS
		9	All	None	None
			1	0.2037	PS
Small	Western Gray Squirrel	2	All	2.469e-10*	PS
			1	NA	NA
			2	0.2058	PS
		4	All	2.2e-16*	PS
			1	2.2e-16*	PS
			2	1.989e-14*	PS
	Black-tailed Jackrabbit	9	All	0.00172*	PS
			1	0.04332*	PS

1: Group1 - Results from model with pseudoabsences >100 m from WVC observations. Similar results were obtained with no buffer for pseudoabsence points.
2: CB = concrete barrier, MG = metal beam guardrail, C = cable barrier, VS = vegetated strip, GS = gravel strip, PS = painted stripe
* Indicates significant value <0.05

Combined district models by animal (deer, coyote, western gray squirrel, black-tailed jackrabbit) resulted in identical findings across the districts for the same species. For deer, western gray squirrel, and black-tailed jackrabbit painted stripe median type is most strongly correlated with WVC (see Figure 4 and Figure 6) while gravel is the strongest for coyote (see Figure 5).

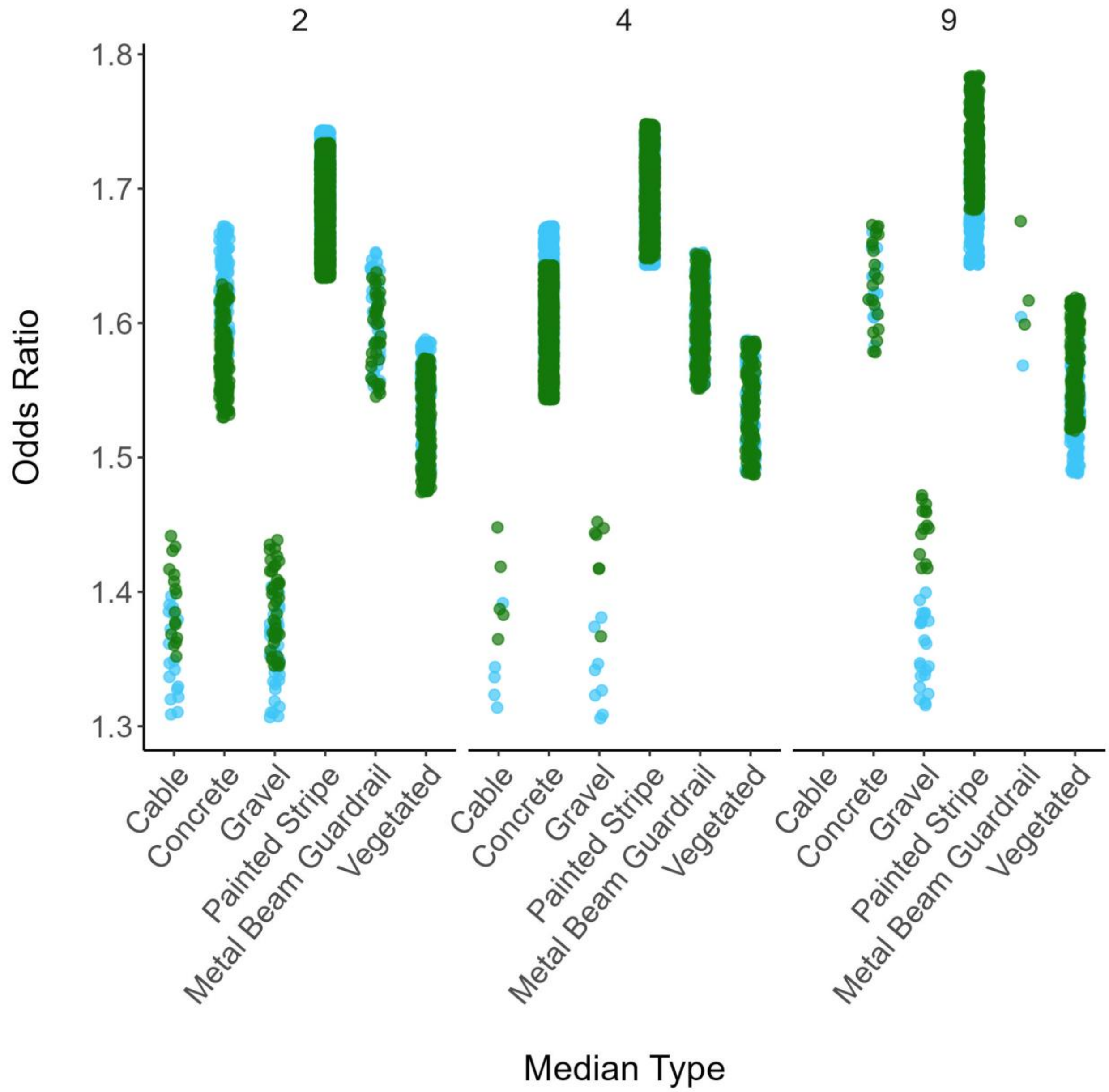

Figure 4. Mule deer model results across Districts 2, 4, and 9 using all data (no spatial groupings). The x-axis includes the median type categories, and the y-axis are odds ratios. Values greater than 1 indicate a positive association, values less than 1 indicate a negative association, and a value equal to 1 indicates no association. Blue dots correspond to the 100m exclusion buffer present and green dots have no exclusion buffer.

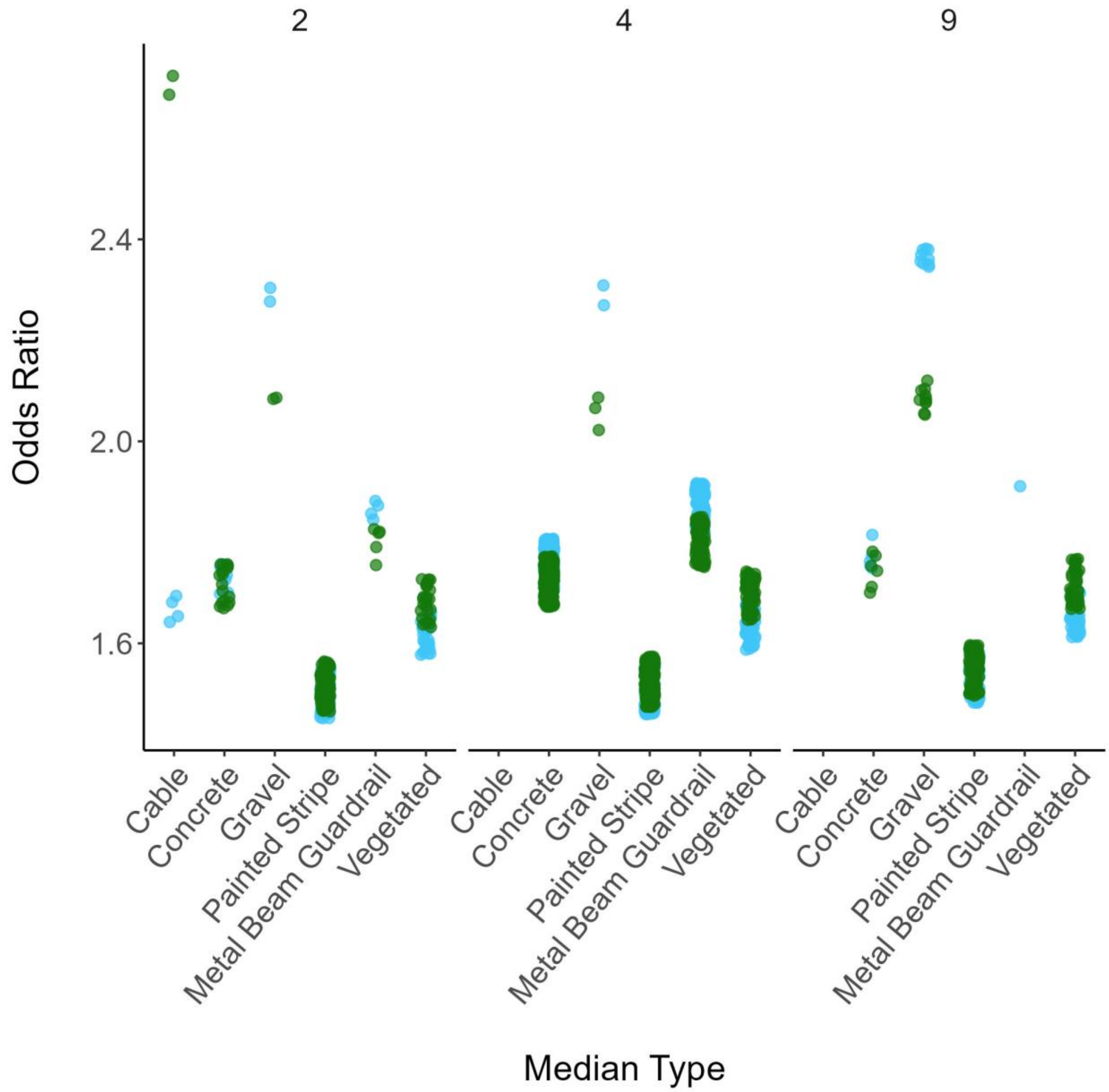

Figure 5. Coyote model results across Districts 2, 4, and 9 using all data (no spatial groupings). The x-axis includes the median type categories, and the y-axis shows odds ratios. Values greater than 1 indicate a positive association, values less than 1 indicate a negative association, and a value equal to 1 indicates no association. Blue dots correspond to the 100m exclusion buffer present and green dots have no exclusion buffer.

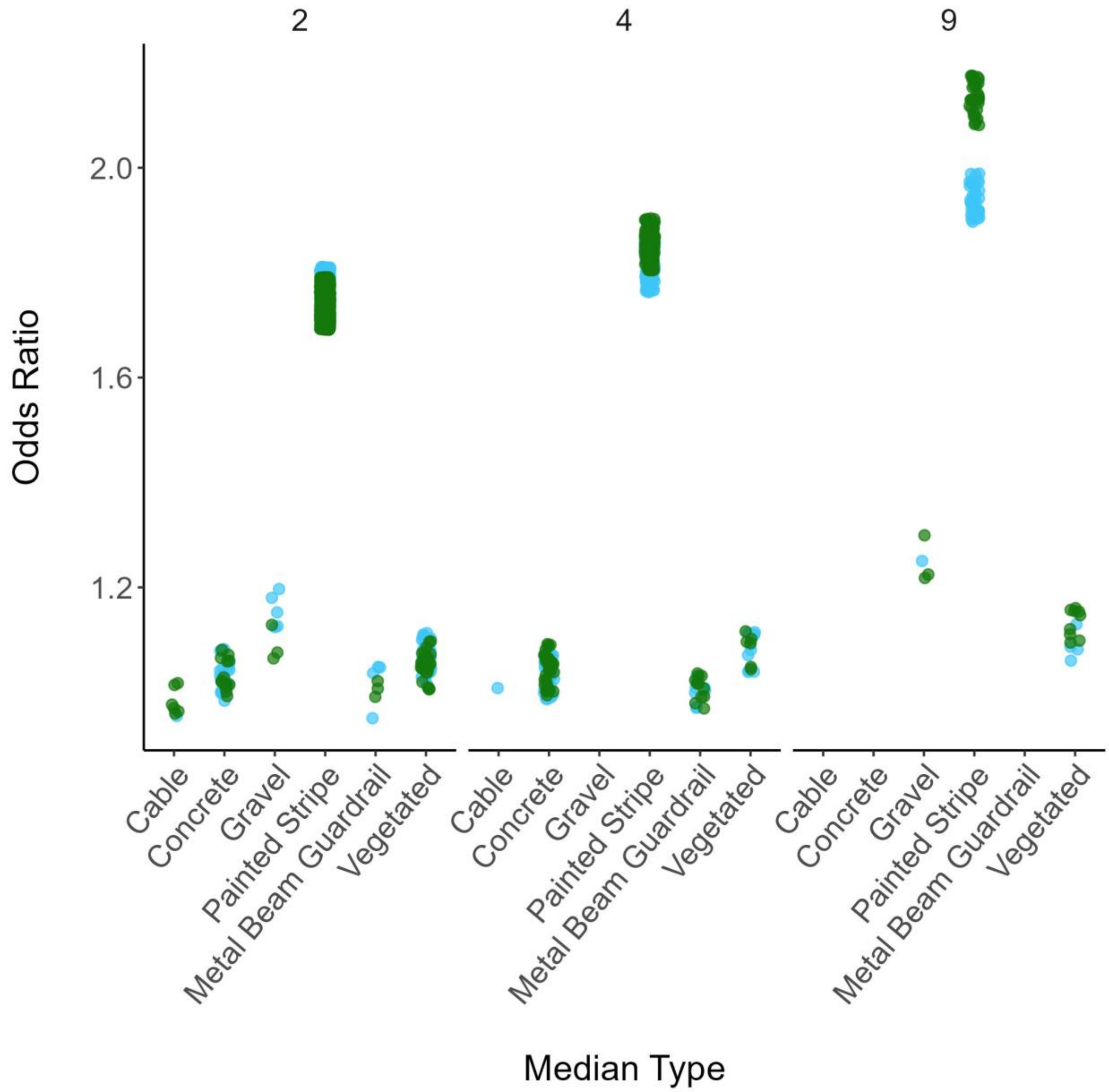

Figure 6. Western Gray squirrel for Districts 2 and 4, Black-tailed Jackrabbit for District 9 model results using all data (no spatial groupings). The x-axis includes the median type categories, and the y-axis are odds ratios. Values greater than 1 indicate a positive association, values less than 1 indicate a negative association, and a value equal to 1 indicates no association. Blue dots correspond to the 100m exclusion buffer present and green dots have no exclusion buffer.

Table 5 shows the pairwise comparison of the effects of different median types on WVC rates, where there was a significant ($p<0.05$) difference. In some cases, there are multiple significant differences (e.g., for mule deer in District 4). For mule deer and coyote, these differences were usually with median types with more visibility having greater rates of

WVC, though this was not always true (e.g., CB/VS comparison in District 4 for both species). For black-tailed jackrabbit, median types with more visibility always had higher WVC rates than no-visibility (i.e., CB), or there was no significant difference. For several District-species combinations, there were no significant differences between WVC rates among median pairs.

Table 5. Pairwise comparison of the effects of median types on WVC (p<0.05)

Species Size	Species	District	Group	Comparison[1]
Large	Mule Deer	2	All	PS/CB, MG/CB
		4	All	CB/VS, PS/MG, PS/VS, MG/VS
		9	All	VS/GS
			1	PS/GS
Medium	Coyote	2	All	VS/PS
			1	None
			2	None
		4	All	CB/PS, MG/PS
			1	None
		9	All	None
			1	PS/VS
Small	Western Gray Squirrel	2	All	PS/CB, VS/PS
			1	NA
			2	None
		4	All	VS/PS
			1	VS/PS
			2	None
	Black-tailed Jackrabbit	9	All	None
			1	None

1: CB = concrete barrier, MG = metal beam guardrail, C = cable barrier, VS = vegetated strip, GS = gravel strip, PS = painted stripe.

Model with Additional Predictors

Table 6 and Table 7 include median type and other predictor variables, such as traffic volume and landcover for District 2, 4 and 9. Table 6 shows the significant predictor variables (p<0.05) within a GLM model comparing WVC rates with median type and other predictor variables for each species across the three Districts individually. Quite often, there were multiple variables that were important in predicting WVC rates. In 3 cases, all for coyote in District 2 or 9, there was only one significant predictor variable. Median type was always an important predictor for mule deer and Western gray squirrel in all Caltrans Districts, but less so for coyote (District 2) and not at all for black-tailed jackrabbit.

Table 6. Significant predictors of WVC rates (<0.05) from GLM model with all predictor variables

Species Size	Species	District	Group	Significant predictors
Large	Mule Deer	2	All	Median, AADT, building, open water, development, barren, shrub, wetlands
		4	All	Median, AADT, building, NHD, forest, shrub, planted/cultivated
		9	All	Median, building, forest
			1	Median, building, development, forest, herbaceous
Medium	Coyote	2	All	Median, open water, barren, planted/cultivated
			1	Forest, shrub
			2	Herbaceous
		4	All	AADT, building, open water, development, forest, herbaceous
			1	AADT, building, open water, forest
		9	All	AADT
			1	Herbaceous
Small	Western Gray Squirrel	2	All	Median, building, development, barren, forest, herbaceous, planted/cultivated, wetlands
			1	NA
			2	Median, building, NHD, open water, development, wetlands
		4	All	Median, building, NHD, herbaceous, planted/cultivated, wetlands
			1	Median, building, development, forest, planted/cultivated
			2	Median, building, NHD, open water, development, forest, planted/cultivated
	Black-tailed Jackrabbit	9	All	AADT, building, developed, shrub
			1	NHD, barren, forest, wetlands

Table 7 shows the significant predictor variables ($p<0.05$) within a GLM model comparing WVC rates with median type and other predictor variables for each species combining the three Districts together. There was a significant positive association (odds ratio >1) with the painted stripe and vegetated strip median types for the deer (large mammal) model. There was a significant negative association (odds ratio <1) with concrete, metal beam guardrail, and vegetated strip median types for western gray squirrels in Districts 2 and 4 and black-tailed jackrabbits in District 9 (small mammal). All significant landcover predictors were neutrally associated (odds ratio = 1) with WVCs.

Table 7. Summary of combination of species results including all districts from GLM model with all predictor variables

Species Size	Significant predictors (<0.05)	Odds Ratio
Large (Mule deer)	Painted stripe[1, 2]	1.45[1, 2]
	Vegetated[1, 2]	1.34[1, 2]
	AADT[1, 2]	1.0[1, 2]
	Building[1, 2]	1.0[1, 2]
	Development[1, 2]	1.0[1, 2]
	Barren[1, 2]	1.0[1, 2]
	Forest[1, 2]	1.0[1, 2]
	Shrub[1, 2]	1.0[1, 2]
	Planted[1, 2]	1.0[1, 2]
	Wetland[1, 2]	1.0[1, 2]
Medium (Coyote)	AADT[1, 2]	1.0[1, 2]
	Open water[1, 2]	1.0[1, 2]
	Development[1, 2]	1.0[1, 2]
	Shrub[1, 2]	1.0[1, 2]
	Herbaceous[1, 2]	1.0[1, 2]
Small (Western gray squirrel & Black-tailed jackrabbit)	Concrete[1]	0.02[1]
	Concrete[2]	0.12[2]
	Metal Beam Guardrail[1]	0.00
	Vegetated[1]	0.06
	AADT[1]	1.0
	Building[1, 2]	1.0[1, 2]
	NHD[1, 2]	1.0[1, 2]
	Open water[2]	1.0[2]
	Development[1, 2]	1.0[1, 2]
	Barren[1, 2]	1.0[1, 2]
	Forest[1, 2]	1.0[1, 2]
	Shrub[1, 2]	1.0[1, 2]
	Planted[1, 2]	1.0[1, 2]

1: 100m exclusion buffer for random points
2: no buffer for random points

Discussion

Our primary findings were that there are effects of median treatments on rates of WVC and that these effects varied by species and to some degree by geographic region (represented by Caltrans District). We disproved the null hypothesis, that there was no effect of median type on WVC rates and suggest that the best alternative hypothesis is H2, that there is an effect of median type on WVC rates and it varies by species and possibly geography.

When presence of any median treatment was evaluated (4), for small animals (i.e., western gray squirrel and black-tailed jackrabbit), the presence of a vegetated or paved median strip was a predictor of higher rates of WVC than presence of a median barrier. This is somewhat in contrast to McLaren et al (2011), who found no impact of presence of vegetated strips on small mammal crossing highways, and similar to McDonald and St Clair (2004), who found an effect of vegetated medians.

For WVC across taxa, Snyder (2014), Kim et al (2021), and Pagany and Dorner (2019) found a generally negative relationship between presence of a median barrier and rate of WVC. We found variation in effect on WVC rate among species and among median types. For a medium-sized animal, coyote, the presence of a metal beam guardrail, or undeveloped median was a significant predictor of WVC. For a large animal, mule deer, we found that the presence of a metal beam guardrail, concrete barrier, or undeveloped median were predictors of WVC. This is in contrast to (Singleton and Lehmkuhi, 2000) who found that deer mortality was greater in the vicinity of vegetated medians. Our finding is also in contrast to suggestions in earlier literature (Malo et al., 2004; Gunson et al., 2011) that the presence of median barriers resulted in lower WVC rates for large mammals. Our results combined with existing literature suggest that there may not be a single simple relationship between median barriers and WVC and instead that there are species-specific and median barrier-specific responses.

Median treatments were also compared with each other in pairwise comparisons (Table 5). For western gray squirrel, vegetated medians were greater predictors of WVC than paved medians and paved medians were greater predictors than concrete barriers. There were no significant differences among median types for black-tailed jackrabbit. For coyote, vegetated and paved medians varied with each other in terms of which was a greater predictor of WVC in Districts 2 and 9, but in District 4 median barriers were greater predictors than paved median. For mule deer, in Districts 2 and 9, vegetated or paved medians were greater predictors of WVC than other median types, whereas in District 4, the relationship was more complicated, with the following approximate ranking of predictors of WVC: CB>PS>MG>VS.

When compared with all predictor variables in a GLM analysis (6), median type was a significant predictor of WVC for western gray squirrel in both Districts 2 and 4, but median type was not a significant predictor of WVC for black-tailed jackrabbit in District 9. For coyote, median type was a significant predictor of WVC in District 2, but not in Districts 4 or 9, where traffic volumes (AADT) were consistent predictors of WVC. For mule deer, median type was always a predictor of WVC, along with distance to nearest building. The second-most consistent predictors were distance to forest and traffic volumes.

Our overall results were that WVC rates for small animals were greatest in the absence of a constructed median barrier, suggesting that small animals may not try to cross a roadway, and thus get hit by traffic when a constructed median barrier is present, as is the case in one study of bobcats (Serieys et al., 2014). The consequence of this could be that highways containing median barriers inhibit small wildlife permeability, unless there are culvert or bridge passageways for the species. For coyote and mule deer in rural Districts (2 and 9), WVC was more strongly associated with lack of a constructed barrier, suggesting that these two species may not be attempting to cross highways with median barriers. In contrast in the more urban District 4, coyote and mule deer WVC was associated with both barrier-containing and undeveloped medians, suggesting that other factors, such as traffic and nearby land cover may be important co-predictors of WVC.

Next Steps

The study painted a relatively clear picture of the effect of median treatment types on WVC rates in California, an important aspect of wildlife permeability. However, it did not address two other primary determinants of wildlife permeability – 1) wildlife behavior approaching and crossing the roadway into the median, and 2) successful wildlife traversing of medians. Wildlife behavior can be characterized as the mechanism by which wildlife permeability can be impacted by median treatments and desired changes made to negative impacts. Wildlife may be successfully crossing median structures, which may not be captured in WVC data.

We suggest three follow-up investigations to fully explore how median treatments are affecting wildlife permeability and how/if negative effects can be mitigated.

1) Development of a generalized linear mixed effects model (GLMM), or random forest model to better evaluate the strength and direction of relationships among species, geography and variable types (including median type). Increase the geographic breadth of the investigation beyond the three Caltrans Districts analyzed. This would require an expansion of the initial effort, but not necessarily new data collection. This would be a good precursor to investigations of individual species behavior on the roadside when faced with different median types.

Management nexus: This analysis is more likely to result in District and species specific results that could help with planning for individual species and single highways.

2) Wildlife behavior can be measured for individual species at low resolution using GPS collars (e.g., for mule deer or puma) and for many species at high resolution using camera traps. Both methods have limitations and advantages. Camera traps set on video or bursts of stills can be used to record wildlife dwell time and behavior within the detection zone. This means that roadside, roadway, and median behavior can be measured in relation to median treatment types for any species triggering the camera. The limitations include: managing false triggers from vehicles and detection area limits. Using GPS collars could provide limited understanding of the movement behavior of individuals of a few large species adjacent to median types. However, the sampling rates are typically much too infrequent to capture individual decisions about infrastructure. For example, at a jogging speed of 5 m/s, a deer or puma would cover 2 lanes and a shoulder in 1-2 seconds, so measuring pausing, running, and changing direction would require very frequent GPS recording (e.g., 1 second interval) and accurate locations. These rates are much more frequent than usual and would require a special study. **We suggest using camera traps to measure wildlife behavior in relation to different median treatments. We also suggest conferring with wildlife scientists using GPS collars about the possibility of very high frequency location sampling.**

Management nexus: This type of study would provide more information about how species of high management and human-safety concern, such as puma, mule deer and elk, behaviorally respond to median types, which could guide median type planning when these species are the targets in particular areas.

3) Constructed medians provide an opportunity to sample wildlife DNA while they are transiting the structures. DNA primers are available at two labs we use for all vertebrates in California, meaning single median treatment samples can be assayed for over 200 terrestrial vertebrates in one analysis. We are carrying out pilot studies of DNA collection in scuppers at the bottom of Jersey barriers to see if they are used by small mammals. Similar collection could occur at cable guard and metal-beam barriers. Different methods could be used for DNA sampling in vegetated medians, which could indicate both occupancy and transiting of the median. **We suggest using DNA sampling to directly determine which terrestrial vertebrates are crossing through median barrier openings, or crossing over vegetated medians.**

Management nexus: This information would be much more precise in terms of species identification than camera trap, or WVC data, both of which are necessarily incomplete, especially in relation to small or rare species. Collecting and analyzing these data would allow environmental planners in Districts to understand which species were impacted, or benefiting from median types and mitigations.

References

Ahmed, I.U. and Ahmed, M.M., 2022. Investigating the Safety Effectiveness of Wildlife–Vehicle Crash Countermeasures using a Bayesian Approach with a Comparison between Carcass Removal Data and Traditional Crash Data. *Transportation Research Record*, p.03611981221083904.

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

Andrews K.M., Langen T.A., Struijk R.P.J.H. 2015b. Reptiles: Overlooked but often at risk from roads. Handbook of Road Ecology. Wiley, New York, pp 271–280

Baker, C., El Hanandeh, A. and Jones, D., 2022. Does wildlife crossing infrastructure work? A case study of three canopy-bridge designs and exclusion fencing from Moreton Bay Regional Council, Queensland. Australian Mammalogy.

Barnum, S., 2003. Identifying the best locations to provide safe highway crossing opportunities for wildlife. Proceedings of the 2003 International Conference on Ecology and Transportation.

Blackburn, A., Veals, A.M., Tewes, M.E., Wester, D.B., Young Jr, J.H., DeYoung, R.W. and Perotto-Baldivieso, H.L., 2022. If you build it, will they come? A comparative landscape analysis of ocelot roadkill locations and crossing structures. Plos one, 17(5), p.e0267630.

Brehme, C.S., J.A. Tracey, L.R. McClenaghan, and R.N. Fisher. 2013. Permeability of roads to movement of scrubland lizards and small mammals. Conservation Biology, 27(4), pp.710-720.

Brehme, C.S., S.A. Hathaway, and R.N. Fisher. 2018. An objective road risk assessment method for multiple species: ranking 166 reptiles and amphibians in California. Landscape Ecology 33:911–935.

Brehme, C. S., Tracey, J. A., Ewing, B. A., Hobbs, M. T., Launer, A. E., Matsuda, T. A., Adelsheim, E.M.C.and Fisher, R. N. (2021). Responses of migratory amphibians to barrier fencing inform the spacing of road underpasses: A case study with California tiger salamanders (Ambystoma californiense) in Stanford, CA, USA. Global Ecology and Conservation, 31, e01857.

Brehme, C., Barnes, S., Ewing, B., Vaughan, C., Hobbs, M., Tornaci C., Gould, P, Holm S.,Sheldon H., and R. Fisher. 2022a. Research to Inform Passage Spacing for Migratory Amphibians and to Evaluate Efficacy and Designs for Open Elevated Road Passages. USGS Cooperator Report to Nevada Department of Transportation, Transportation Pooled Fund Program Project P342-20-803. https://www.pooledfund.org/Document/Download?id=11851

Brehme C.B., Barnes, S., Gould, P., Ewing, B., Vaughan, C., Hobbs, M., Tornaci, C., Holm, S., Sheldon, H., Fiutak, J., and Fisher, R.N. (unpublished manuscript, in review). Elevated road segment (ERS) passage design may provide enhanced connectivity for amphibians, reptiles, and small mammals.

Case T.J., Fisher R.N. 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

Clevenger, A. and M. Huijser. "Wildlife Crossing Structure Handbook: Design and Evaluation in North America." (2011).

Clevenger, A.P. and Kociolek, A.V., 2013. Potential impacts of highway median barriers on wildlife: State of the practice and gap analysis. *Environmental management*, *52*(5), pp.1299-1312.

Cooper, J.M., 1999. Mitigation of impacts to wildlife and wildlife habitat for advanced construction candidate segment of Cache Creek to the Rockies program. *Cache Creek to the Rockies Program, BC, Canada*.

Cramer, P., J. Kintsch, L. Loftus-Otway, N. Dodd, K. Andrews, T. Brennan, P. Basting, J. Gagnon, L. Frazier, and L. Sielecki. 2022. The Strategic Integration of Wildlife Mitigation into Transportation Procedures: Practices, Partnerships, and Next Steps. Report 700-18-803A to the Nevada DOT as part of Pooled Fund Project TPF-5(358).

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

Dodd Jr, C.K., Barichivich, W.J. and Smith, L.L., 2004. Effectiveness of a barrier wall and culverts in reducing wildlife mortality on a heavily traveled highway in Florida. *Biological Conservation*, *118*(5), pp.619-631.

Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. Annual review of ecology, evolution, and systematics, pp.487-515.

FHWA. 2016. Highway Performance Monitoring System: Field Manual. Office of Highway Policy Information Published Date: 2016-12-01 URL : https://rosap.ntl.bts.gov/view/dot/50372 (Accessed January 2, 2024).

Foresman, K.R. 2004. The effects of highways on fragmentation of small mammal populations and modifications of crossing structures to mitigate such impacts (No. FHWA/MT-04-005/8161). Montana. Department of Transportation. Research Section.

Forman R.T., Sperling D., Bissonette J.A., Clevenger A.P., Cutshall C.D., Dale V.H., Fahrig L., France R., Goldman C.R., Heanue K., Jones J.A. 2003. Road ecology. Science and Solutions.Island Press, Washington

Glista D.J., DeVault T.L., DeWoody J.A. 2008. Vertebrate road mortality predominantly impacts amphibians. Herpetol Conserv Biol 3(1):77–87

Gunson, K.E., Mountrakis, G. and Quackenbush, L.J., 2011. Spatial wildlife-vehicle collision models: A review of current work and its application to transportation mitigation projects. *Journal of environmental management*, *92*(4), pp.1074-1082.

Helldin J.O. 2022. Are several small wildlife crossing structures better than a single large? Arguments from the perspective of large wildlife conservation. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 197–213. https://doi.org/10.3897/natureconservation.47.67979

Hu, W. and Donnell, E.T., 2010. Median barrier crash severity: Some new insights. *Accident Analysis & Prevention*, *42*(6), pp.1697-1704.

Jackson, S. D., Langen, T. A., Marsh, D. M., and Andrews, K. M. 2015. Natural history and physiological characteristics of small animals in relation to roads. Roads and ecological infrastructure. Concepts and applications for small animals. Johns Hopkins University Press, Baltimore, 21-41.

Jarvis, L. E., Hartup, M., and Petrovan, S. O. 2019. Road mitigation using tunnels and fences promotes site connectivity and population expansion for a protected amphibian. European Journal of Wildlife Research, 65(2), 1-11.

Jochimsen D.M., Peterson C.R., Andrews K.M., Gibbons J.W., 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

Kim, K., Yi, Y., Woo, D., Park, T. and Song, E., 2021. Factors influencing Roadkill Hotspot in the Republic of Korea. *Proceedings of the National Institute of Ecology of the Republic of Korea*, *2*(4), pp.274-278.

Kintsch, J. and P. Cramer. 2011. Permeability of existing structures for terrestrial wildlife: a passage assessment system (No. WA-RD 777.1). Washington (State). Department of Transportation. Office of Research and Library Services.

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

Malo, J.E., Suárez, F. and Díez, A., 2004. Can we mitigate animal–vehicle accidents using predictive models?. *Journal of applied ecology*, *41*(4), pp.701-710.

Martinig, A.R. and Bélanger-Smith, K., 2016. Factors influencing the discovery and use of wildlife passages for small fauna. *Journal of Applied Ecology*, *53*(3), pp.825-836.

Martinig, A.R. and Mclaren, A.A., 2019. Vegetated highway medians as foraging habitat for small mammals. *Wildlife Society Bulletin*, *43*(2), pp.317-322.

Matos, C., Petrovan, S. O., Wheeler, P. M., and Ward, A. I. (2019). Short-term movements and behaviour govern the use of road mitigation measures by a protected amphibian. Animal Conservation, 22(3), 285-296.

Matthews, K. R., and Pope, K. L. 1999. A telemetric study of the movement patterns and habitat use of Rana muscosa, the mountain yellow-legged frog, in a high-elevation basin in Kings Canyon National Park, California. Journal of Herpetology, 615-624.

McDonald, R.W. and St. Clair, C.C., 2004. The effects of artificial and natural barriers on the movement of small mammals in Banff National Park, Canada. *Oikos*, *105*(2), pp.397-407.

McLaren, A.A., Fahrig, L. and Waltho, N., 2011. Movement of small mammals across divided highways with vegetated medians. *Canadian Journal of Zoology*, *89*(12), pp.1214-1222.

Ortega, B., F. Shilling, N. Dodd, T. Longcore, A. Cassady, and M. Davis, 2021. Morongo Pass wildlife Connectivity, Study and Recommendations Report to Caltrans. Pp. 249.

Ottburg, F. G., and Van der Grift, E. A. 2019. Effectiveness of road mitigation for common toads (Bufo bufo) in the Netherlands. Frontiers in Ecology and Evolution, 7, 23.

Pagany, R. and Dorner, W., 2019. Do crash barriers and fences have an impact on wildlife–vehicle collisions?—An artificial intelligence and GIS-based analysis. *ISPRS International Journal of Geo-Information*, *8*(2), p.66.

R Core Team 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/

Riley, S.P., Brown, J.L., Sikich, J.A., Schoonmaker, C.M. and Boydston, E.E., 2014. Wildlife friendly roads: the impacts of roads on wildlife in urban areas and potential remedies. In *Urban Wildlife Conservation* (pp. 323-360). Springer, Boston, MA.

Russo, B.J. and Savolainen, P.T., 2018. A comparison of freeway median crash frequency, severity, and barrier strike outcomes by median barrier type. *Accident Analysis & Prevention*, *117*, pp.216-224.

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., Van Der Ree, R., Cunnington, G.M., Fahrig, L., Findlay, C.S., Houlahan, J., Jaeger, J.A., Soanes, K. and van der Grift, E.A., 2015. Experimental study designs to improve the evaluation of road mitigation measures for wildlife. Journal of Environmental Management, 154, pp.48-64.

Rytwinski, T., Soanes, K., Jaeger, J.A., Fahrig, L., Findlay, C.S., Houlahan, J., Van Der Ree, R. and van der Grift, E.A., 2016. How effective is road mitigation at reducing road-kill? A meta-analysis. PLoS one, 11(11), p.e0166941.

Schmidt, B. R., Zumbach, S., Mitchell, J. C., Jung Brown, R. E., and Bartolomew, B. 2008. Amphibian road mortality and how to prevent it: a review. Herpetological conservation, (3 (Cha), 157-167.

Schmidt, B. R., Brenneisen, S., and Zumbach, S. 2020. Evidence-based amphibian conservation: A case study on toad tunnels. Herpetologica, 76(2), 228-239.

Serieys, L.E., Rogan, M.S., Matsushima, S.S. and Wilmers, C.C., 2021. Road-crossings, vegetative cover, land use and poisons interact to influence corridor effectiveness. *Biological Conservation*, *253*, p.108930.

Singleton, P.H. and Lehmkuhl, J.F., 2000. *I-90 Snoqualmie Pass wildlife habitat linkage assessment* (No. WA-RD 489.1,).

Sinsch, U. 2006. Orientation and navigation in Amphibia. Marine and Freshwater Behaviour and Physiology, 39(1), 65-71.

Southwood, A., and Avens, L. 2010. Physiological, behavioral, and ecological aspects of migration in reptiles. Journal of Comparative Physiology B, 180(1), 1-23.

Smith, L.L. and C.K. Dodd Jr. 2003. Wildlife mortality on US highway 441 across Paynes prairie, Alachua County, Florida. Florida Scientist, pp.128-140.

Snyder, S.A., 2014. Examining the impacts of State Route 101 on wildlife using road kill surveys and remote cameras. PhD. Dissertation, California Polytechnic University, San Luis Obispo.

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

Taylor, P.D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos, pp.571-573.

Tscharntke, T., J.M. Tylianakis, T.A. Rand, R.K. Didham, L. Fahrig, P. Batáry, J. Bengtsson, Y. Clough, T.O. Crist, C.F. Dormann, and R.M. Ewers. 2012. Landscape moderation of biodiversity patterns and processes-eight hypotheses. Biological reviews, 87(3), pp.661-685.

Vaughan, C., Barnes, S., Brehme, C.S, Liang, C.T., Brown, C. Unpublished manuscript (currently in review). Spatial analysis of Yosemite toad road mortality in Sierra National Forest, California.

Villalobos-Hoffman, R., Ewing, J.E. and Mooring, M.S., 2022. Do Wildlife Crossings Mitigate the Roadkill Mortality of Tropical Mammals? A Case Study from Costa Rica. Diversity, 14(8), p.665.

Warnock-Juteau K, Bolduc V, LoScerbo D, Anderson M, Daguet C, Jaeger JAG (2022) Co-use of existing crossing structures along roads by wildlife and humans: Wishful thinking? In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 235–270. https://doi.org/10.3897/natureconservation.47.73060

Wilcove, D.S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. BioScience, 48(8), pp.607-615.

Data Summary

Products of Research

1. Existing wildlife-vehicle collision data from the California Roadkill Observation System.
2. New WVC observations during field work.
3. Remaining cited data are available from other, non-UCD sources.

Data Format and Content

All WVC observation data includes date/time, animal species, and location (latitude/longitude) information.

File types are .xlsx (MS-Excel).

Data Access and Sharing

The datasets are available on the Road Ecology Center on a dedicated project page: https://roadecology.ucdavis.edu/research/projects/median-barriers

Reuse and Redistribution

There are no restrictions on data use. Citation for the dataset is:

> Road Ecology Center, 2025. Dataset of wildlife vehicle collisions associated with median treatments. https://roadecology.ucdavis.edu/research/projects/median-barriers.