ACCOMODATING HUMAN AND SMALL ANIMAL USE

OF WASHINGTON WILDLIFE PASSAGE STRUCTURES

by

Sean Patrick Greene

A Thesis
Submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
June 2015

This Thesis for the Master of Environmental Studies Degree

by

Sean Patrick Greene

has been approved for

The Evergreen State College

by

____
Dina Roberts, Ph.D.
Member of the Faculty

____
Date

ABSTRACT

Accommodating Human and Small Animal Use
of Washington Wildlife Passage Structures

Sean Patrick Greene

It is well documented in the road ecology literature that transportation infrastructure has a negative impact on wildlife populations through habitat and population loss and fragmentation (Soulé, 2001). The development of wildlife-focused passage structures like bridge underpasses, culverts, and overpasses has proven effective at mitigating some of these impacts of roads on ungulates and other large mammals (Kintsch & Cramer, 2011). However, two populations that are incorporated into the use community for these structures, namely human pedestrians and small animals, are often discounted as incidental (Niemi et al., 2012). In partnership with the Washington State Department of Transportation, this study used data collected from camera traps to observe the communities using a variety of passage structures across western Washington. This study explored how human use impacted wildlife use and what passage elements appeared most preferable to smaller mammalian vertebrates. Ultimately, this study identified 26 different species that successfully passed at least one individual through a passage structure over this annual cycle, including 19 smaller vertebrate species (<50 lbs.). In addition, increased human use rates demonstrated a likely negative impact on wildlife of any size or behavioral type. The number of individuals and species richness differed between paired sites suggesting that the presence of permanent running water without available dry paths is a significant barrier to use, increased cross-sectional area is preferred by humans and larger animals while the smaller confines of culverts seem to have higher small animal use rates, and the availability of elevated paths to cross above ground level may facilitate and encourage small animal movement through structures. Future research should be considered to better gather a full understanding of the types of use these structures receive and how they could be designed in the interests of promoting use by humans, large mammals, and small wildlife equally.

Table of Contents

List of Figures

List of Tables

Acknowledgements

This thesis is the end result of numerous hours devoted to data collection, analysis, research, and writing over the previous twelve months. Yet, as this final draft stands completed, it owes more to the support network that surrounded me throughout this process than to any personal time spent in the execution. I stand eternally grateful for the help and encouragement that I have received from a number of avenues and can only hope that the end result of this thesis proves worthy of the people who helped in its creation.

I must thank the Washington State Department of Transportation's Environmental Services Office for allowing me the use of the imagery data collected as part of their Habitat Connectivity Program that proved so instrumental in reaching the conclusions presented in this thesis. In particular, thank you to Marion Carey, the Fish and Wildlife Program Manager, who hired me as an intern in July, 2014, and tasked me with servicing the program's many wildlife cameras, laying the groundwork upon which this thesis has been built. In addition, I owe a great deal of thanks to Kelly McAllister, Wildlife Biologist, who supervised my work throughout my time with the agency, offering sage advice, invaluable input, and welcome companionship on countless occasions. His efforts have made me a better scientist and his revisions and review of this thesis' earlier drafts went a long way in making it a more presentable project. I also thank Stacey Plumley, GIS Analyst, for opening my eyes to computer tools and fields of study that were beyond my imagination.

The faculty and students of the Master of Environmental Studies program at The Evergreen State College also played a fundamental role in this success. First and foremost, thank you to Dina Roberts, my thesis reader and sounding board, was heavily involved with every step of this project, offering endless support and feedback regardless of the hurdles that appeared throughout the process. I say this without hyperbole when I say that without Dina, this thesis would simply not exist. I thank Kevin Francis and Erin Martin for helping me to think and act in a scientific manner and expanding the horizons of my knowledge. I thank Carri LeRoy for being the only person ever to prove capable of making the vagaries of statistics seem straightforward. I also thank Mike Ruth for his enthusiasm and limitless knowledge of GIS, both traits that I hope to have retained a little of.

Finally, the appreciation that I hold for the support that I have received throughout my life, deserved or not, from my family is infinite. My family, especially my parents, have never stopped believing in my abilities, nor have they ever ceased to push me to becoming the person and professional that they know be capable of becoming. For that, I have no words to accurately express my gratitude.

Chapter 1: Literature Review

Introduction

Road ecology is a field of science that began when scientists and road managers realized that the increasing rate of road construction and use brought people's needs into sharp conflict with wild animal populations' use of habitat near roadways. While this observation may seem intuitive today, 1996 marked the relatively recent point when the first major scientific conference focusing on this discipline was held in Orlando, Florida.

Over 4 million miles of public roadways exist across the United States touching the lives of virtually every one of the 320 million people living in this nation, and yet this arena of science is still underexplored (Forman et al., 2003). A search the word "ecology" for the years 1956 (when the Interstate Highway System was formed) to the present in the Evergreen State College database cataloging peer-reviewed journal articles resulted in 227,884 results; when the search was altered to look for "road ecology" with the same date range, however, the number of results dropped to 2,212, less than 0.01% of the previous total. Despite increased attention to this topic from many state and federal agencies in recent years, this traditional oversight does not seem to be fading away as when the same search was run for the years 1996 (when the first road ecology conference was held) to present, the percentage remained unchanged. Most of these interested agencies have direct ties to roadway management, such as the Washington State Department of Transportation (WSDOT), and deploy a suite of tools to study the topic. In the case of WSDOT, the agency uses 40-50 wildlife cameras and a dozen radio collars to observe animal movements near state roads. They also maintain a carcass removal database that dates back to 1973 tracking the locations of roadkill for selected species, primarily ungulates and large carnivores, throughout the state. The limited time and tools available to scientists in this field are devoted largely to Wildlife Vehicle Collisions (WVCs) and habitat connectivity initiatives.

Current Road Ecology Research

WVCs are a major and continuing issue of interest for those who study road ecology due to their prevalence and clear impact on human society. As of 2007, an estimated 1-2 million WVCs involving large animal species occur annually in the United States, accounting for approximately 26,000 human injuries, 200 human deaths, and $8.4 billion in damages each year (Huijser et al., 2007). The impressive scope of this negative interaction between people and wildlife has perhaps dominated the traditional discussion of how to manage the overlapping spheres of wildlife habitat and human development. Washington State bears a smaller share of these events than many other states as WSDOT employees remove an average of 3,700 large mammal carcasses from state roads annually, but it remains an area of interest for the agency (Washington State Department of Transportation, 2015). In addition, the Washington State Patrol records an annual average of 1,100 WVCs a year resulting in more than 150 human injuries (Washington State Patrol, 2015). This suggests that the actual number of annual WVCs involving large animals in Washington State may approach or exceed 10,000 with damages numbering in the tens of millions of dollars based on the observed report deficiency rate in other studies (Huijser et al., 2007). WVCs are a difficult problem to tackle given the wide variety of factors that can contribute to the problem. Human factors, such as vehicle speed, traffic volume, and driver awareness require social movement to reduce.

Environmental factors, such as seasonality, weather, and time of day are beyond any powers of control. Finally, wildlife dynamics are animal-centric, like animal abundance, animal species, and habitat connectivity and can be difficult to directly influence (Litvaitis & Tash, 2008).

Habitat connectivity became a driving focus of study in part as a result of these worries over WVCs and other concerns related to fragmentation effects on wildlife in general. Human vehicle traffic on roadways continues to grow unabated and, as a result, there has been a sustained, continuous increase in WVCs of 8-20 percent per year nationwide, though this has not been yet observed in Washington (Gaskill, 2013). There is only so much that can be done to make drivers more aware of the dangers and to take preventative actions, so policy makers and scientists have expanded efforts to assess why wildlife cross roadways despite the obvious repulsive forces like noise, light, pollution, and the risk of injury or death (Fahrig & Rytwinski, 2009). The massive network of roads in the US was planned according to human concerns like minimizing cost and travel distance. As a result of this narrow viewpoint, people built straight, artificial lines of non-permeability, fragmenting historic animal ranges. Animals of various sizes and species still needed to move around their habitat to find food, mate, and migrate, leaving dangerous crossings of roadways as their sole option (Forman et al., 2003). This inclusion of paved, trafficked roadways into their habitat ranges places animals into a position of attempting to adapt behaviors trained through generations for a specific terrain to one that can be wholly unsuited for their survival. Having understood the source of the problem, namely that roadways impede animal movement through once-contiguous habitat, the challenge was then how to allow for free and easy movement of animals below, or sometimes above, roadways. Passage structures specifically designed for animal use are usually presented as the solution to this issue of roadways breaking apart preexisting habitat connections, but they are often unnatural structures placed in an environment where they can be unappealing to wildlife.

Wildlife Passage Structures

The goal of maintaining habitat connectivity for wildlife species near roadways in an effort to reduce WVCs has been addressed by a number of wildlife passage structures. These structures are engineered to funnel animals to points where they can move across roadways without having to come into contact with vehicles. Wildlife passage infrastructure has four primary types of composition, each with its own subtypes, which are used by transportation agencies to control animal movement: underpasses, overpasses, barriers, and one-way structures.

By far the most common passage structure put into use by transportation agencies are underpasses, specifically bridges and culverts. These structures provide an excellent balance of effectiveness, customization, and convenience for both human and wildlife use. Bridges have a long historical use in road construction to traverse rivers and valleys, and have the added benefit of allowing for animal passage beneath roads, though the open space beneath is more of an engineering decision than an ecological one. Bridge designs vary, however; a large bridge with mostly open space beneath it can be very successful in reducing fatalities for megafauna like black-tailed deer (*Odocoileus hemionus*), elk (*Cervus canadensis*), black bear (*Ursus americanus*), and moose (*Alces alces*). One project in which highway construction elected to incorporate such bridge designs into the construction plan in North Carolina observed that white-tailed deer (*Odocoileus virginianus*) use of the areas were underpasses were put into place with accompanying fencing increased 6.7 times when compared to the baseline passage rate for the areas prior to construction. As a result of the great success in shifting most deer movement into the relative safety of an open bridge underpass, deer fatalities dropped by 58% (McCollister & van Manen, 2010). These extensive bridges have been shown to be the preferred passage method for ungulates and carnivores due to the high visibility they offer (Kintsch & Cramer, 2011). Ungulates likely prefer the clear sightlines as they rely upon speed and quick reaction time to elude predators. Smaller bridges that present wildlife with a more enclosed space are no less effective, but are used by a different target population: one that prefers a low-visibility habitat. Medium sized and small mammals, reptiles, and amphibians prefer heavy cover, especially at the entrances to the bridge to break line-of-sight and can find the confinement of a narrow passage more tolerable (Kintsch & Cramer, 2011). When presented with the decision, wild ungulates and certain other megafauna will actively avoid the use of smaller, confined passages, electing to brave passage over the roadways instead (Rodriguez, Crema, & Delibes, 1996).

Carnivores have proven to be more difficult to predict as preferences for passage structures differ distinctly by species and even by individual, with sex and age playing significant roles in influencing passage rates (Clevenger et al., 2002). Carnivores with less tolerance to human-related disturbances, either through noise or physical disturbance, such as grizzly bears tend to favor open bridges with ready access to covering foliage on either end. Carnivores that are more resilient to human influence like cougar (*Puma* *concolor*) and black bear have instead shown a marked preference for more compact passage structures with open ground on the ends (Clevenger & Waltho, 2005). In addition, habitat preferences gleaned from carnivore predation ranges cannot be assumed to be accurate for passage structures as the evidence that predators use bridges as traps to hunt prey is "scant, largely anecdotal and tends to indicate infrequent opportunism rather than the establishment of patterns of recurring predation" (Little, Harcourt, & Clevenger, 2005). Because of all of these caveats attributed to carnivore passage, the consensus opinion is to ensure that when passage structures are installed, a variety of forms and sizes are used (Clevenger & Waltho, 2005).

Culverts are similar to bridges in that they come in many forms and sizes that can be tailored to target a particular species of interest, but can be placed wherever needed without installing an expensive bridge. They can range in size from small, water-only pipes on the order of 1 foot in diameter (though these are of limited utility for animals, they are still used when water movement is the sole concern of the project) to 10 or more feet in diameter. These spiral corrugated metal or concrete pipes were originally intended to allow for streams, runoff, and stormwater to pass under roadways in the interests of driver safety and roadway preservation, but have proven to be widely used by various animal species (Kintsch & Cramer, 2011). In particular, they are the primary tool used by transportation agencies to maintain fish passage routes via streams that intersect with roadways (Anderson et al., 2012). Their primary role as a method of transporting water can negatively impact the use of these culverts by wildlife though, with smaller carnivores exhibiting significantly decreased passage rates when culverts carried water more than 3 cm deep or covering more than 70% of the culvert base (Serronha et al., 2013). The diversity of preferences for carnivores is still evident when dealing with culverts though, as larger carnivores do not seem to be deterred much by water in culverts (Craighead Institute, 2010). While these structures are widely-used and offer many benefits, they can be difficult to design for a multiple-use system in which people and animals of many sizes can find equal access to safe, convenient passage. The simple solution, building more culverts and bridges to take into account the requirements of various species on an individual basis, is stymied by rising costs and shrinking budgets in transportation agencies.

Overpasses offer much more in the pursuit of multiple-use structures, but are held in check by a commensurate increase in costs. These “land bridges” are a relatively new phenomenon in road design as they attempt to create a more natural passage system. An overpass is a structure placed over a road, creating a tunnel for drivers, that is topped by soil and vegetation, characteristic to the surrounding environment, reconnecting the habitat on either side of the roadway into a single ecosystem (Smith, 2011). These provide an exceptional passage route for birds, mammals, reptiles, and insects, though fish are largely excluded as moving water features cannot transverse the sloped sides of the overpass. The shallow ponds, coarse woody debris, and dense vegetation that may be part of the design of overpasses can also serve as useful habitat for amphibians (Owens et al., 2008). In addition, evidence suggests that the largest forms of wildlife, such as moose, distinctly prefer to use overpasses in place of even the most open of underpasses when given the option (Huijser et al., 2013). This is understandable given that these structures are open to sunlight, precipitation, and certain elements of the natural system. These factors, when combined with screening vegetation placed along the edges of the overpass to hide the traffic from animal view, can create an exceedingly comfortable passage system for most terrestrial animals (Kintsch & Cramer, 2011). It is even possible to incorporate stationary water features into the design, though running water is currently impossible without significant, expensive feats of engineering ingenuity. Washington is currently developing an innovative wildlife overpass along Snoqualmie Pass East on I-90 that aims to be one of the first of its kind in the world (Figure 1). The 15-mile stretch of road that includes the 800-foot long Price/Noble Creek Overpass is being built at a cost of approximately $100 million and the overpass is notable for the devoted effort being made to include every aspect of the surrounding environment so as to make the structure virtually indistinguishable from the natural habitat for wildlife (Smith, 2011).

Barriers and one-way structures are often used in conjunction with overpasses or underpasses to dissuade wildlife from crossing roadways and convincing them to use passage structures instead. Barriers commonly take the form of fencing, but the category can include elevated walls or cement barriers. Essentially barriers exist to deter any passage attempts by wildlife and are normally placed along the edge of roadways. In that position they serve as a vital part of any population movement control as they artificially boost passage rates at desirable locations where structures have been built to accommodate this process. In one project in Montana, effective use of fencing, underpasses, and one-way structures saw the number of deer that crossed the roadway at a underpass increase 5.2 times from 1,732 a year before the structures were in place to 9,084 afterwards (Huijser et al., 2013). Another project, this one from WSDOT, built approximately 9 miles of fencing along US97 Alternate Route north of Wenatchee, WA along with several one-way structures to reduce the number of deer and bighorn sheep

WVCs along the roadway. In the 15 years prior to the project, deer and sheep carcasses removed from the targeted stretch of highway had reached densities of 10.8/mile/year and 1.0/mile/year, respectively. After the project, carcass removal rates fell to a respective 0.3/mile/year and 0.0/mile/year (McAllister et al., 2014). The effectiveness of barrier wall and culvert combinations is not limited to larger species such as these, though, as a project in Payne's Prairie State Preserve, Florida using this method saw a year-to-year 93.5% decrease in road fatalities for amphibians following construction (Dodd, Barichivich, & Smith, 2003). While fencing in particular has proven highly effective at enhancing areas of safe passage to wildlife, it is not foolproof. Animals will only travel parallel to roadways along fencing for so long before trying to force a passage if no structure presents itself. There is a strong correlation between lower mortality rates and wildlife fencing along roadways, but at distances too far away from an accompanying passage structure, mortality rates will begin to rise again as animals attempt to jump the fence, unaware an alternative exists (McCollister & van Manen, 2010).

One-way structures include jumpouts and wildlife guards. Jumpouts consist of ramps built at equal level with roadways that allow for animals that have been trapped on the wrong side of a barrier to escape the roadway and return to the natural environment, but their vertical height where they intersect fencing does not allow for movement in the opposite direction. Jumpouts are not included as a means of regular animal traffic as, ideally, the fencing and passage structure system has been designed effectively enough that no individual finds itself on the roadside of the fencing. Instead, they exist as a sort of emergency exit for wildlife. Wildlife guards are a series of spaced metal pipes placed over a hole dug into an arterial road that connects with a major roadway that is otherwise enclosed by fencing. Wildlife guards are necessary to allow vehicles to enter or exit the major roadway without undercutting the effectiveness of barriers. Ungulates can observe the space between the metal pipes and understand that their hooves will fall in between and so do not attempt passage, but smaller animals or larger animals with padded feet like carnivores are not as easily dissuaded. Aside from most animal species (though a minority of gross individuals due to the abundance of ungulates) being able to traverse wildlife guards with relative ease, there have also been observed instances of ungulates attempting to cross wildlife guards and risking injury through a trapped leg or a fall. Alternatives to wildlife guards such as radio-triggered fencing with transmitters delivered to private individuals on the far side of the barrier have been discussed, but are generally dismissed due to the increase in complexity, cost, and maintenance.

Small Animal Concerns

The vast majority of road ecology research is centered on reducing WVCs and, therefore, passage structures are heavily weighted towards megafauna, particularly ungulates. The negative impact that roads have on the many remaining forms of wildlife, like small mammals, birds, reptiles, and amphibians, is somewhat uncertain given the general lack of interest and funding. Surveys of small animal roadkill are few and far between and it is unclear if any transportation agency in the country maintains a comprehensive database covering carcass removals for small animals outside of a select few charismatic species like bobcats (*Lynx rufus*) and bald eagles (*Haliaeetus leucocephalus*). No agency has a freely-available report on small animal roadkill at any rate and discussions with representatives from multiple state agencies in the Pacific Northwest have suggested that the impact of WVCs on small animal populations is not a current interest area in internal research. New research in this field is starting to raise alarms, however, as it appears that the relationship between these species and roadways is just as perilous as that of the more well-understood species like deer. As an example of the potential danger of this oversight, a recent study has suggested that as many as 340 million birds are killed on US roads annually as a result of vehicle strikes, 4-6 times greater than the previous 2005 estimate of 60-80 million (Loss, Will, & Marra, 2014; Erickson, Johnson, & Young, 2007). Meanwhile, the 0.25-0.5 million birds that die in wind turbine strikes annually receive heavy media attention and research funding. A confident estimate of just how many small animals are killed by WVCs every year doesn't exist in the current research. Ideally, this could be a scenario where steps can be taken by scientists to solve a problem whose scope is not yet understood.

One effect that roads have on wildlife that is better covered by the existing literature is the way in which they alter habitat preferences for small mammals and reptiles. There exist animals, such as the hedgehog (*Erinaceus europaeus*), that see significantly reduced population densities near roadways. In the hedgehog's case, population density dropped by a full 30% near roadways due to unfavorable habitat and vehicular strikes (Huijser & Bergers, 2000). Perhaps counterintuitively, not all small species populations are negatively impacted by roadways and some, in fact, see a positive impact. Vultures and other scavengers are attracted to the roadkill produced by WVCs as a source of food, but are capable of avoiding vehicles, leading to a net population gain. Other animals actually derive a benefit from the disturbance provided by traffic; small mammals settle on roadway verges to use the noise and movement of traffic to scare away predators while avoiding the roads themselves (Fahrig & Rytwinski, 2009).

Maintenance efforts to sustain roadways clear of vegetation generally leads to a regular regime of mowing roadway verges by transportation agencies. This regular mowing creates a vegetation community composed primarily of grasses that are kept short, serving as prime habitat for seed-eating small mammals (Oxley, Fenton, & Carmody, 1974). These road verges have become such a preferable habitat for some species like the wood mouse (*Apodemus sylvaticus*) that studies have shown that they can prefer habitat close to roads over habitat distant from roads by up to a 9:2 ratio (Ruiz-Capillas, Mata, & Male, 2013).

This positive habitat selection preference by some small mammal and reptile species for road proximity can have significant negative results, though. Not every animal that elects to live in road verges is capable of avoiding vehicles, leading to greatly increased collision rates. Medium sized predators such as raccoons (*Procyon lotor*) and bobcats with large movement ranges often come into conflict with roads that pass through their habitat area. These high-movement animals are often put doubly at risk as they predate on the small mammals that settle on road verges (Fahrig & Rytwinski, 2009). Nesting animals have shown a similar tendency to lay eggs or rear young on road verges. Higher proportions of juvenile mice have been found closer to roads than further away in Spain and up to 30% of freshwater turtle species in northwestern Florida build nests directly adjacent to the highway shoulder where soil and vegetation conditions are often optimal for nesting (Ruiz-Capillas, Mata, & Male, 2013; Aresco, 2005). In the case of the turtles in particular this has become an issue as WVCs are resulting in nearly twice as many female turtles being killed as males due to this nesting behavior (Aresco, 2005). These behavioral traits present a unique issue in developing a beneficial passage system for smaller animals as some traditional methods like hazing or population culling that have been used with some success on larger species are of minimal utility (Huijser et al., 2007). Hazing, the use of negative harassment techniques like odors and noises to discourage animal presence, and population culling, the killing of a portion of a local population usually through hunting, are not as effective with smaller animals due to their small size and large population numbers.

Small Animal Structure Elements

If some animals are actively seeking out habitat adjacent to roadways, efforts to design effective passage structures for them becomes all the more paramount. As previously discussed, the needs of small animals versus those of large mammals with regard to these structures do not necessarily overlap and there is no one-size-fits-all solution. There exists a variety of research on the topic of small animal passage structure design, but most studies are very specific in the scope of species studied, mandating that the lessons learned should be extrapolated to other species with caution.

In Hungary, researchers found that amphibians with migration paths that crossed roadways seldom used existing culverts with only 0.5% of the observed populations making use of the structures with the rest passing directly over roads. Those individuals who did pass through the culverts exhibited a clear preference towards older, larger culverts (160-170 cm) as compared to newer, smaller culverts (40-60 cm) by approximately a 5:1 ratio (Puky, Mester, & Mechura, 2013). Woltz, Gibbs, & Ducey (2008), in an impressive multiple species analysis for passage structure preferences among amphibians and reptiles, concluded along similar lines, recommending tunnels larger than 500 cm in diameter lined with soil or gravel and accompanied by fencing at least 0.6 m in height. A community event in Amherst, Massachusetts was put at risk in 1987 when observers noted that the annual spring migration of salamanders was resulting in an increasing number of salamanders being killed by traffic along a two-lane road that the animals needed to cross. Activists pushed for amphibian passage structures with designs similar to those suggested by existing research. Several agencies combined funds to construct two “salamander tunnels,” small, moist culverts with a slotted top to allow light to penetrate along the full length, and fencing to block salamanders from crossing the road. Citizen scientists studying the results found that salamanders, even at extreme ends of the funneling fence, managed to find the tunnels and more than 75% of those that reached the tunnels successfully used them to cross (Jackson & Tyning, n.d.). The Payne’s Prairie Nature Preserve working group that formed in central Florida with the goal of tackling a stretch of US 441 that paced the state in roadkill reports, particularly for amphibians and reptiles. This group observed that containers used by zoos and private pet owners for these species tend to have a lip at the top that prevents reptiles and amphibians from climbing out. They adopted this lip concept by adding it to the top of a 1.8 mile low wall along the stretch of highway, drastically cutting down roadkill rates as amphibians and reptiles were effectively funneled to culverts (Southall, n.d.).

Small mammals have particular needs in a passage structure as well. Unlike their larger relatives, small mammals actively avoid large, open spaces when presented with the option under bridges and in culverts. Deer and elk rely upon speed and agility to avoid predation and thus need clear lines of sight to give them ample time to be alerted to the presence of a predator. Smaller mammals use speed as a defense of last resort and instead need cover and enclosed spaces to allow them to hide from predators. If the passages get too small, however, some small mammals will eschew them so as not to feel confined or constricted (Kintsch & Cramer, 2011). In a study in Montana, researchers took baseline data of the passage rates of several small mammal species through large, open underpasses of a 7x4 meter area. Cover in the form of dead tree branches and other plant debris were added to some of the underpasses, resulting in a 42.9% increase in passage rate versus control culverts (Connolly-Newman et al., 2013). In addition, mammals with particularly small body sizes are often unwilling use culverts where water dominates the passage due to their reliance on terrestrial environments for ease of movement (Wolff & Guthrie, 1985). This presents a problem given that habitat connectivity concerns are often secondary to water control when electing how and where to construct underpasses. The solution is often an economic and utility compromise that draws from observation of natural behavior patterns for the targeted species. In a natural system, they use logs and branches to pass over areas of water when necessary. Placing similar debris in culverts would be counterproductive to maintaining clear waterways and only a stop-gap measure until the wood was washed away or rotted. Instead, wildlife shelving has been developed. This shelving can be installed on the sides of bridges and culverts and allows for continued use of culverts even when partially filled with water. In another case study in Montana, 14 small mammal species were observed to use a series of culverts when dry but virtually none did when the culverts were wet. After installing wildlife shelving, all 14 species were observed making use of them while the culverts were wet, effectively solving one of the issues impeding small animal underpass use, under their specific set of circumstances (Foresman, 2004). As this shelving is installed approximately halfway up the side of a culvert, water passage and access for maintenance staff remain unimpeded.

Ultimately, the hurdle inhibiting efficient small animal passage structure development isn't a lack of ideas, but a lack of implementation and analysis due to insufficient funding. While adding cover and shelving were both impressively successful in the described case studies, the demands of each scenario are defined by the species, habitat, and peculiarities present. It is for this reason that post-activity observation is paramount so that more knowledge can be added to the collective scientific consciousness. A project in Ontario, Canada that put into place a number of mitigations to aid in habitat connectivity and animal passage for reptiles was observed afterwards to have no significant change in population abundance (Baxter-Gilbert, Lesbarrères, & Litzgus, 2013). This particular project may have had other benefits that the researchers were unaware of, such as improved genetic diversity due to more interrelationship between population segments, or benefits that will only become apparent following a greater period of observation. In the short-term, the researchers were able to make recommendations for improving the effectiveness of mitigation measures based on their methodology. Because of post-project analysis, this project, which the authors stated failed to meet their objectives, can now contribute to future developments as part of the rigorous testing of various mitigation measures. This also highlights the need for further reporting of negative results in academic journals; as experimental passage designs are put through field testing, there are bound to be failures. The only way to ensure that these failures are not repeated is to share them and analyze what went wrong.

Effect of Human Use

Perhaps no single factor, however, has a greater impact on wildlife usage of passage structures than human presence (Gagnon et al., 2011). When WVCs occur on highways in regions distant from residential areas, human pedestrian presence is often discounted, but city borders continually expand as the human population grows, suggesting that these isolated stretches of roadway will become less so over time. Much like the other variables associated with fauna passage rates, human presence has a different impact dependent on the form of that presence and the species of wildlife being observed. For most species, the matter is a determination of the degree of the negative impact that humans have, but for some high-disturbance prey species, human presence can actually be a benefit (Fahrig & Rytwinski, 2009). This benefit is largely derived from human presence serving to lower use by predator species. In the interests of maintaining high passage rates across a number of species, protecting wildlife populations at an ecosystem level, and mitigating WVCs, human influence must be minimalized. Research in the field has shown that any current or future underpass designs "will be minimally successful if human activity is not managed" (Clevenger & Waltho, 2000). While both carnivores and ungulates have shown some preferential use for structures with little human activity, the cause of this avoidance is different for the two groups of interest (Yanes, Velasco, & Suárez, 1995; Macdonald, 1998).

For carnivores, the issue is one of habitat disturbance and influence rather than an individual-level interaction. Many carnivores exhibit behavior patterns that lend towards an avoidance of large numbers of human individuals. Large carnivores will make use of habitat with limited human activity, but shun habitat that has been significantly altered by human presence or where human activity reaches a particularly high level. This occurs because humans tend to startle game species away and can change the land-cover type into an unnatural form (Dellinger et al., 2013). Carnivores and humans also differ in temporal use patterns; specifically, the fact that humans primarily make use of passage structures during the day while carnivores tend to be nocturnal in nature, combined with the secretive and solitary natures of many carnivores means that an in-person interaction with a carnivore for human pedestrians is unlikely (Rodriguez, Crema, & Delibes, 1996). Carnivores may often remain active during the daytime in natural environments, but evidence suggests that they prefer nocturnal activity when in proximity to human settlements (Hemson et al., 2009). Some large carnivores relevant to Washington, specifically black bear and cougar exhibit this change in use patterns. Research in western Washington shows that when they interact with residential human regions, they traverse the area rapidly and primarily at night in an effort to limit their interaction with an environment that no longer suits their needs (Kertson et al., 2011). Carnivores remain sensitive to human interference in areas near hunting ranges or alterations to hunting trails (Yanes, Velasco, & Suárez, 1995). With carnivores, therefore, the issue is not so much occasional human passage, but the threat that a continued, substantial human presence can irrevocably alter the habitat through prey exclusion, activity levels, noise, or physical impact so as it make it unsuitable for carnivores (Gagnon et al., 2011). A study analyzing the interrelationship between humans, gray wolves (*Canis lupus*), and elk in Jasper National Park, Alberta, Canada showed that elk, one of the primary prey species for wolves, developed a habituation to human activity and suggested that the elk remained near human populations as a source of refuge from predators (Shepherd &

Whittington, 2006). While carnivores, like other animals, can adapt to landscape changes, human use tends to depreciate an area for carnivores and many prove unable to adapt as easily to human interactions, driving carnivores to regions with less human intrusion.

Compared to a general avoidance by larger carnivores to human presence, ungulates have shown a greater ability to adapt to sharing habitat with humans. In point of fact, non-carnivores in general show an impressive aptitude for shifting their home ranges based on human influences and can even find human proximity advantageous in certain circumstances. Ungulates have activity patterns that occur throughout both the day and the night, with most activity in Pacific Northwest ungulates like elk taking place during daylight hours (Ensing et al., 2014). Elk are largely crepuscular in their feeding habits and there is an increased rate of movement during these periods, making them likely occasions for direct human interaction (Ager et al., 2003). Ungulates do not therefore necessarily have the benefit of a temporally independent use period for passage structures, meaning in-person interactions are far more frequent, "causing run backs, hesitation, and eliciting visual alarm responses" when they come into contact with humans near passage structures (Pedevillano & Gerald Wright, 1987). Rather than interact with humans directly, non-carnivores will often adjust their ranges so as to best cohabitate with human influences and do so with great proficiency. When starlings in New York City, which find the urban setting ideal for finding food, were pressed to find a place to nest away from the constant presence of humans managed to identify "an area with fewer humans afoot than any within miles of the city," yet still within the heart of the urban extent, revealing their ability to adapt behaviors to habitat aspects (Leedy, Franklin, & Hekimian, 1975). In addition, Gagnon et al. (2011) found that white-tailed deer use of passage structures increased over time, even with a constant human presence, as the population adapted to existing conditions. This suggests that human influence is not a primary concern for ungulates deciding where to move within their range as they can habituate themselves to shared environments. When designing multiple use passage structures with ungulates and other prey species in mind, the focus must be on ensuring as little direct interaction with people as possible (Mata et al., 2008).

The vast majority of highway passage structures like bridges and culverts are designed with a primarily human transportation benefit or benefit in mind: to traverse rivers or gorges, cross over or under other roads or railroad tracks, or to allow for floodwater to pass beneath busy roadways to protect infrastructure projects. Research delving into the relationship between wildlife and road passage structures should, as a result, take into account the human element. Human pedestrian benefits of these structures are secondary to this prioritized transportation need and are sometimes nothing more than opportunistic in utility for this purpose. Yet this pedestrian use does occur and failure to account for how human pedestrians impact efforts to encourage wildlife use of passage structure will result in a significant decline in positive results.

Human Structure Elements

As understanding of how human presence around and use of passage structures impacts wildlife expands, scientists and road managers have experimented with methods to alleviate some of the stress involved with passage by multiple species. These efforts largely fall under one of two camps: structure placement and structure design.

In an ideal world, human and wildlife use of passage structures could be completely divested from one another due to geographic separation of the populations. In reality, human development and infrastructure expansion creates an every-expanding region of overlapping habitation with wildlife, necessitating adaptation on the part of the infrastructure designers and wildlife biologists. As previously noted, the primary tool that biologists can use to direct wildlife towards preferable passage points is fencing or barrier walls, though passage structures must be placed somewhat regularly along the fencing lest the animals attempt to break through the fence (McCollister & van Manen, 2010). The solution is not as simple as merely fencing entire highway or placing bridges and culverts liberally as if resources were unlimited.

When, as is commonly the case, bridges and culverts must be placed in areas of human presence, they should be located as far from human settlements as is reasonable to best promote wildlife passing without hassle through underpasses and along overpasses (Olsson, Widén, & Larkin, 2008). In the common event that faunal populations are too closely intertwined with human populations to make this a practical possibility, these structures could be built in areas with a high degree of private land ownership (Rodriguez, Crema, & Delibes, 1996). Private land has the primary benefit of reducing the accessibility of passage structures for human pedestrians as human foot traffic is heavier in public areas. Placing the actual structure on private land can prove problematic in that the ability of an agency to manage the structure for wildlife is negatively impacted, but in public areas with a high degree of surrounding private land ownership, it can help minimize human pedestrian presence. Reducing the number of human pedestrians who make use of a structure is the most efficient way of making such a structure viable for animal use, but that number need not be reduced to zero. A number of studies have shown that so long as human passage rates remain relatively low, there is no measurable impact on wildlife passage rates (Mata et al., 2008; Yanes, Velasco, & Suárez, 1995). Planners must also account for the fact that as general human disturbance of a passage lane decreases increasing the utility of the structure for wildlife, the likelihood of direct physical contact between any single human pedestrian and an animal increases (Macdonald, 1998).

Developing structures for occasions where wildlife and humans must use the structures simultaneously presents several unique challenges, but has become an increasingly familiar issue in construction. As more roads are built and existing roads are expanded with more lanes, human pedestrians have found themselves equal with wildlife in their diminished ability to transit by foot (National Public Radio, 2014). Some have suggested that this co-use is best accommodated by making use of paired structures of a relatively close geographic proximity. In a number of cases, humans and wildlife have voluntarily segregated themselves to one of the other structure (Olsson, Widén, & Larkin, 2008). Observational evidence suggests that human walkers elect to make use of the structure that is most convenient or best fits their needs, while wildlife will choose the least-disturbed passage available (Macdonald, 1998). Should these populations be forced to make use of the same structure, the primary method of management that is advised is screening vegetation and other visual barriers. Placing screening above an underpass, thus shielding wildlife from the sight and some of the sound of passing vehicular or pedestrian traffic above, has been showing to reduce visible disturbance by half (Phillips, Alldredge, & Andree, 2001). Additionally, placement of screening vegetation at the entrances to bridges and culverts can serve to discourage human use and limit their ability to disturb the terrain (Gagnon et al., 2011). In cases of high passage rates, such as a when a popular walking trail runs underneath a bridge, planners have suggested designing the ground to have a vertical separation so that humans and wildlife make use of parallel, but separate trails (Macdonald, 1998). This method can also be combined with screening vegetation that runs the length of the underpass, ensuring minimal sight lines between the human and animal trails.

The full recognition of the interrelation among both human and non-human populations of interest that make use of passage structures has been recent, but as the field has expanded, it has become evident that human pedestrians and animals are both making common use of what were initially viewed as largely vehicle transportation structures. Even now, when there is a major interest in developing wildlife-centric elements like ecosystem overpasses to maintain habitat connectivity, human presence is not discounted. Innovation in this field is focused on ensuring the co-use is incorporated into design documents and all species' needs are accounted for (National Public Radio, 2014).

Literature Review Summary and Thesis Research Questions

Human population growth and associated development will continue at an increasing rate in the foreseeable future in the US and Washington State (United States Bureau of the Census, 2000). The field of road ecology can then be expected to grow in kind as scientists further explore the negative impact that road construction has on wildlife populations and habitat connectivity. Bridges, culverts, underpasses, and overpasses, originally designed purely with engineering interests in mind, have increasingly become tied to ecological concerns and especially to enhancing connectivity for the habitat used by wildlife populations. This partnership that allows for habitat maintenance as an element of human development, rather than as a contrary element, must be preserved.

In the interests of preserving and further developing a holistic approach to road construction that takes into account the habitat and population requirements of all affected species, it is imperative that scientific study of these issues not be limited to ungulates and large carnivores merely because they are involved with the WVCs that endanger human lives and property. The hundreds of millions of WVCs that go unrecorded each year in the US due to the size of the animal struck are having an unknown, but surely significant, impact on wildlife populations. There are conspicuous gaps in the existing research regarding important aspects of road ecology that must be filled. The following research seeks to work towards that goal by:

1. Assessing and analyzing the impact that human use has on animal use of wildlife passage structures.
2. Summarizing several years' worth of data on 8 unique structures throughout Washington State and discuss the biodiversity implications.
3. Highlighting the impact that several specific design elements of structures have on small vertebrate use rates.

There is no clear "right" answer when discussing passage structure design, nor is there even a clear hierarchy or priorities. Some researchers claim that location of construction is preeminent, while others insist on specific structural dimension, and others yet focus on the makeup of the community using these locations (Foster & Humphrey, 1995). This research will endeavor to suggest that a detailed, site-specific knowledge is the best tool available to a planner. Upon completion, this research will be shared with the Washington State Department of Transportation to ideally inform future construction projects on how best to accommodate non-target species like small vertebrates and humans when designing or retrofitting passage structures.

Chapter 2: Analysis of Human and Small Animal Use of Passage Structures

Study Introduction

Every year, an estimated 1-2 million vehicles collide with large animals in the United States, prompting numerous studies investigating how to mitigate this source of conflict between human and wildlife travel requirement (Huijser et al., 2007). Millions of dollars are spent by state and federal agencies developing strategies and structures to maintain habitat connectivity for these ungulates and large carnivore in an effort to reduce WVCs. Road construction negatively affects wildlife in ways beyond simple road mortality by limiting genetic diversity among populations by placing impassible barriers and fragmenting traditional desirable habitat ranges (Forman et al., 2003). Resource and transportation agencies have recognized this issue as a natural resource management priority, even going so far as to spend tens of millions of dollars to design, build, and maintain bridges, culverts, and wildlife-focused overpasses that mimic surrounding habitat and allow for wildlife to pass below or above busy roadways (Smith, 2011; O'Malley, 2004). This effort is well-intentioned and has proven effective in numerous cases in reducing roadway mortality for large mammalian species by offering preferable alternatives to crossing the road at grade (Hartmann, 2003; Dodd et al., 2004). The use of these structures is not limited to specifically targeted species like deer and elk, however, as human pedestrian use and small animal use occur at relatively high levels (Hartmann, 2003; Connolly-Newman et al., 2013). Historically, it has made sense to focus wildlife passage structure research on the large mammalian populations responsible for so much property damage and risk to human life, but the positives that these structures offer to small animals in terms of limiting roadkill and promoting habitat connectivity is deserving of future study.

At the highest estimate, less than 2 million large mammals are killed annually in the US as a result of WVCs, but as many as 340 million birds are struck and killed by US drivers every year and untold millions of small mammals, amphibians, and reptiles likely share that fate (Huijser et al., 2007; Loss, Will, & Mara, 2014). No reasonable estimates of the total number of smaller animals killed by vehicles exist, this despite an increasing awareness of the importance that roads play in habitat selection and reproduction pressures in small animals (Ruiz-Capillas, Mata, & Male, 2013; Aresco, 2005). What is known, however, is that dry paths under road bridges and through underground culverts have proven very effective in reducing roadkill numbers for small mammals, amphibians, and reptiles, especially when paired with fencing or other methods to funnel population movements (Huijser & Bergers, 2000; Niemi et al., 2012). Existing research shows that these structures are effective in moving small wildlife safely across roadways, especially when efforts are made to accommodate their particular needs with elements like elevated crossing paths and entrance coverage (Jackson & Tyning, n.d.; Connolly-Newman et al., 2013). The current breadth of study still requires more observations of what particular elements appeal to which species and how passage rates differ by species groups.

Human use of passage structures is also perhaps more overlooked than it should be. Human pedestrian passage through these wildlife crossing structures has a largely negative effect on the likelihood that animals of any size will elect to make use of them (Clevenger & Waltho, 2000). Recognizing this problem, most current research largely suggests methods to limit human use either by placing structures in locations where human use is unlikely, specifically distant from known settlements, or by actively restricting human use (Hartmann, 2003; Rodriguez, Crema, & Delibes, 1996). In the interest of promoting wildlife use, these strategies may be ideal, but they are not necessarily realistic in many cases as road construction continues at pace with human development in previously-natural areas, making human and animal co-use increasingly likely (Gunson, Mountrakis, & Quackenbush, 2011). Most current studies emphasize that human presence limits animal use of crossing structures, either through direct physical interactions, noise pollution, or habitat alteration (Smith, 2003; Pedevillano & Gerald Wright, 1987; Gagnon et al., 2011). Given the undue influence that humans have on animal use, then, it is important to analyze just how deleterious this effect is and to find ways to promote co-use.

This study uses existing camera data gathered as part of the Washington State Department of Transportation's Habitat Connectivity program observing existing bridge underpasses and culverts across Washington State. The goal of this research is to better understand the use communities of these structures and attempt to observe how the interactions between human and wildlife populations combined with structural dissimilarities between sites influences what species make use of these structures and how often they successfully cross.

Materials and Methods

Study Origination

As part of WSDOT's Habitat Connectivity policy directive affirming the agency's focus on protecting environmental systems and working towards the maintenance of traditional habitat ranges for wildlife, since 2011 WSDOT has deployed cameras on bridges and culverts across the state to study how wildlife use these structures. These data were collected primarily with the goal of reducing large mammalian passage across roadways. However, during processing of the imagery data, it became apparent that these passage structures are used by a variety of species that far exceeds the scope of the initial study topic. The research in this project is intended to explore the role that bridges and culverts play in population movements for those other species, specifically small wildlife and human pedestrians. The data used in this paper were gathered from a selection of the dozens of cameras that WSDOT has deployed throughout the state of Washington since that initial offering in 2011 and were analyzed with the goal of developing structural elements that will better facilitate co-use. At the least, this information allows for a better understanding of the true number of species and patterns of use that center around bridges and culverts.

Site Identification and Camera Trap Installation

One of multiple WSDOT projects studying wildlife mortality on state highways involved performing statistical hotspot and kernel density analysis of WSDOT's Carcass Removal Database to determine where the highest rates of WVC clustering were present throughout the state. The analysis was performed on data from the years 2009-2013 and included all deer roadkill collected from state highways by WSDOT maintenance personnel during that period, accounting for 17,588 records (McAllister & Plumley, 2015). Deer were selected as the species of interest because this database only tracks large animals large enough to pose a risk to humans through WVCs and, of the tracked species, deer represented 95% of the recorded carcasses. Through statistical and geographic information system analysis, WSDOT was able to identify portions of the state highway system with the highest rate of clustering of WVCs for deer (Figure 2). These locations were then narrowed to places within a half-day's drive of WSDOT headquarters in Olympia to guarantee ease of access for servicing of cameras by eliminating the potential of spending multiple days on each monthly service. A number of potential sites were scouted with an eye towards identifying regions of likely wildlife use of passage structures and preference was given to locations with multiple distinct structures that were separated, yet close enough to justifiably be considered paired. Five sites were finally selected offering insights into a range of environmental, structural, and community factors. Site were located in the Puget Sound region west of the Cascades, in the mountains of the Cascade Mountains, in a valley within the same mountain range, and the drier region east of the mountains. These sites have a combination of bridges and culverts of various sizes and placement and exhibit unique use patterns, especially in terms of percentage use by humans.

Once locations appropriate for the proposed study had been designated, motion-triggered, infrared wildlife cameras were installed in positons where they offered a clear view of each structure of interest. Four models of camera were used throughout the duration of this study. Initial cameras were Reconyx PC85 Professional Color IR models, but as the project expanded, new installations primarily made use of modern Bushnell

Model 119476 and Reconyx HC600 HyperFire High Output Covert IR models. A grant attained in the beginning of 2015 allowed for the purchase of a large number of Reconyx PC900 HyperFire Professional IR cameras and the older, less reliable models, are gradually being replaced with the PC900 models in the field as the older models begin to fail due to age. As this project moves on past the timeframe of this specific study, the cameras deployed in the field will continue to be swapped out with newer models as technology progresses.

Three methods of installation were used depending on the structure being observed and the local terrain: utility box installation, tree mounting, and Telespar mounting (Figure 3). For utility box placement, cameras were disguised in steel utility boxes and set in a concrete foundation of about 18-27 kg with a sheathed bike cable and padlock combination attaching the camera to the cement base and a bolt and nut holding the camera in place within the utility box. The front face of the utility box was screwed into place and locked externally with a second padlock. For tree mounting, cameras were encased in metal housing frames and bolted to a tree through the use of a thick metal bracket. The front face of the casing was secured with a padlock. Telespar mounting was functionally similar to tree mounting, but the frame was bolted to a metal Telespar post so that the camera could be closer to the ground (Sullivan, 2014). All cameras were programmed with electronic code locks so that unauthorized access to the programming or data was made more difficult. Camera installations were all camouflaged, either as an electric utility in the case of the boxes or through the use of paint in the case of the frames, in an effort to reduce their visibility to human pedestrians to avoid vandalism or theft.

Study Area

For the sites selected for this study, data has been collected from 21 cameras which observed 9 structures at 5 sites in various parts of Washington State. In the interests of protecting ongoing studies from theft or other disturbance, only general locational information is provided here. The first, “Western Forest Trail”, was located west of the Cascade Mountain range in a forested area of the Puget Sound climate zone. The second and third sites, “Cascades Wet Culverts” and “Cascades Dry Culvert” were located in the Cascades Mountain Range, in high-elevation forests. The fourth site, named “Cascades River Valley,” was situated in one of the Cascade Mountains’ many river valleys, providing for a unique ecosystem segment to analyze. The final location, “East Dry Forest,” could be found on the eastern slopes of the Cascades, in a climate with far less precipitation than the other sites. These sites were chosen for their roles as WVC hotspots as defined by WSDOT data, locations of continuing concern for habitat connectivity, their possession of multiple close, but distinct paired passage structures, and to offer perspective on a variety of ecoregions (Figure 4).

Western Forest Trail

Western Forest Trail is a popular running and bicycling trail near a town of less than 10,000 people. The trail runs north-south between the verges of the highway and a sizeable river. This area is heavily forested and, while it stands only a few hundred feet above sea level in elevation, has ample mountainous terrain in the surrounding region. This location lies to the west of the Cascade Mountain Range, meaning it shares the climate of much of the area around the Puget Sound, namely mild, wet winters and warm, dry summers. These environmental factors combine to offer excellent habitat to ungulates. High ungulate populations near Western Forest Trail combined with the high traffic volumes on nearby roadways have made this stretch of highway a hotspot for WVCs.

A 1976 steel and concrete bridge with approximately 10 feet of vertical clearance underneath is the structure under observation for this study area (Figure 5). This structure was built by WSDOT to allow for a highway crossing over the local river. A six-foot-high (1.8 m) fence has been in place for some time to prevent wildlife from moving onto the highway, but the fencing is in disrepair at some spots, so wildlife of all sizes can occasionally be found on both sides. Columbia black-tailed deer (*Odocoileus hemionus columbianus*) and elk in particular make common use of this area due to the easy accessibility of the river and the riparian vegetation (Sullivan, 2014). Dikes, in place on both sides of the river, offer relatively level, unobstructed paths of travel that are attractive for animal passage.

East Trail

Two Reconyx HC600 HyperFire cameras were installed on trees along the east side of the river on 8/1/2012 observing the pedestrian trail and the riverbank. The cameras were placed at the top of an embankment less than 100 m from the river and had separate fields of view. This side of the river is a popular recreation area for the nearby residential population, with joggers, cyclists, fishers, and bathers all making regular use. These cameras and brackets were recovered on 8/13/2014 after 743 days of service due to the completion of the desired length of observation.

West Trail

Two Reconyx HC600 HyperFire cameras were installed on trees along the western bank of the river on 12/26/2012, observing the bridge's abutment and pier. The cameras lay within 100 m of the river and have some overlap in field of view. These cameras were installed when it was recognized that despite the east trail offering an ideal passage opportunity for the recorded ungulate population in the area, very few detections were being made due to high human use. This side of the bridge had very little human use and contained open area surrounded by screening vegetation. The cameras and accompanying equipment was removed on 6/19/2014 after 541 days of service due to the completion of the desired length of observation.

Cascades Wet Culvert

Cascades Wet Culvert allows for the passage of a small creek to pass beneath a highway in the Cascades from south to north. This creek persists year-round but the rate of flow is highly seasonal. The structure under observation at this site is a cement double-box culvert with each opening being approximately 6 ft. x 4 ft. and 60 ft. long (Figure 5). The culvert is found in a forested area with rocky terrain on the banks of the stream. The eastern of the paired structures is consistently filled with several inches of water but the western of the paired structures remains clear of water during the dry summers and occasionally carries a small amount running water during the wet seasons. The substrate of the passage is covered with stones of various sizes. While there is heavy vegetation on either side of the structure, there is no screening foliage between the creek and the highway.

A single Telespar-mounted Reconyx HC600 camera was installed here on 4/22/2014 observing the south side of both box culverts. This camera was placed approximately 3 feet above the ground adjacent to the creek bank. The most recent recorded data for this camera were taken on 4/13/2015, representing 357 days of service, and this camera remains in place as of this writing.

Cascades Dry Culverts

This study site is located in an evergreen forest within the Cascade Mountain Range. This site offers a unique necessity for habitat connectivity as the surrounding region is actually located between the westbound and eastbound portions of a large highway. This site is mostly undeveloped, but the few residences in the area are closely located to the structures of note.

The structures being observed at this site are corrugated steel culverts that span the westbound half of a highway (Figure 5). There is a significant embankment between the entrances to the culverts and the highway, meaning that traffic sight and sound is mitigated. The vegetation at the entrances of the culverts is largely salmonberry apart from smaller brush, so the area is well screened during the warmer growing season, but sparser during the winter. The wildlife in the area are almost universally smaller due to the compacted habitable area between the separated highway segments.

West Culvert

Two Reconyx PC900 HyperFire cameras are located on either end of this culvert with the southern, tree-mounted one being installed on 6/19/2014 and the northern, Telespar-mounted one being installed on 3/9/2015. This culvert is approximately 6 feet wide, 8 feet high, and 200 feet long, moving moderately uphill from south to north. A small stream is present on the southern end of this culvert, but no water runs through the actual pipe. This site is also relatively commonly used by human climbers who park on a forest road on the southern side and traverse to a climbing wall on the northern side. The most recent recorded data for these cameras were taken on 4/13/2015, jointly representing 299 days of service, and these cameras remain in place as of this writing.

East Culvert

Three Reconyx PC900 HyperFire cameras are located on either end of this culvert with the first southern, tree-mounted one being installed on 6/19/2014, the northern, tree-mounted one being installed on 8/13/14, and the second southern, Telespar-mounted one being installed on 9/18/2014. The number of cameras in place gradually increased as resources became available with the goal of capturing as much data as possible. This culvert is approximately 5 feet wide, 5 feet high, and 200 feet long, moving moderately uphill from south to north. No water is found on either end of this culvert and it remains dry year-round. There is more vegetation coverage at this site and small wildlife make regular use of woody debris to approach the culvert before crossing. The most recent recorded data for these cameras were taken on 4/13/2015, jointly representing 299 days of service, and these cameras remain in place as of this writing.

Cascades River Valley

The river valley within the Cascades selected that includes this site covers a portion of the east-west oriented US Route 12. The studied bridges are located within a valley at an elevation of approximately 1,000 ft.

This river valley is a prominent area for agriculture and ranching as the flat, riparian terrain is well suited to the industry. The surrounding environment to these bridges is largely grassland and pasture with riparian zones that flood during wetter seasons. The relatively sparse human population combined with floodplain soils that makes domestic farm animals so prosperous also encourages a large population of wild ungulates. These ungulates travel across the grasslands from one fragmented forest patch to another. There are two bridges being observed at this site, one that spans a river and a second built over a common path of seasonal flooding, but is otherwise covering dry ground (Figure 5).

Main Bridge

Three Reconyx PC85 Professional cameras are located near this bridge with two utility box cameras being installed on 12/29/2011 on either side of the bridge and a further utility box camera being installed on the eastern bank on 4/24/2013. This structure is a large bridge with more than 15 feet of clearance and ample open space under the roadway. A major river runs constantly beneath the bridge with embankments on either side, blocking passage from east to west. The western bank is covered with heavy vegetation, especially blackberry, while the eastern bank is more defined by tall grasses. The eastern bank borders a fenced-in cattle ranch that regularly impacts wildlife passage in a negative manner. The most recent recorded data for these cameras were taken on 3/24/2015, jointly representing 1182 days of service, and these camera remain in place as of this writing.

Overflow Bridge

Two Bushnell Model 119476 cameras are located near this bridge with the first Telespar-mounted one being installed on 9/3/2013 observing the north face of the bridge and a second Telespar-mounted camera being installed beneath the bridge on 5/22/2014. This structure is a smaller bridge with approximately 8 feet of clearance. This bridge was designed to accommodate floodwaters that would otherwise cover the roadway, but remains dry outside of severe flood events. The area around this bridge is covered with tall grasses and is bordered by ranchland on either side. The most recent recorded data for these cameras were taken on 3/24/2015, jointly representing 568 days of service, and these camera remains in place as of this writing.

East Dry Forest

The East Dry Forest camera site is found along a north-south oriented highway east of the Cascade Mountains. The climate and environment of this area is complex. As the Cascades border this region to the west, the area surrounding this camera location falls under the rain shadow effect. The land is arid and mostly defined by Ponderosa Pina, brush, and grass, with extensive forested areas to the north as the elevation climbs.

The stretch of road encompassed by this study area is a likely place for WVCs due to a large population of black-tailed deer that move through the dry forests and grasslands and interact with the moderately-trafficked 2-lane highway (McAllister, & Plumley, 2015). Much of the traffic that travels along this highway is compositionally dominated by industry. Many of the vehicles are semi-trailer trucks moving goods between distant cities and there are relatively fewer smaller vehicles due to the limited human settlement nearby. A paired bridge and culvert are being observed at this site (Figure 5).

Bridge

Four Reconyx PC85 Professional cameras are located around this bridge with two tree-mounted cameras being installed on 12/3/2012 on either side of the bridge along with two accompanying utility box cameras installed on 4/2/2013. This structure is a large bridge with more than 15 feet of clearance, but has narrow, steep rip-rap abutment armoring that border closely to the creek, impacting passage during high-water marks. US97 Creek, which this bridge spans, varies considerably by season, as it rises high enough to negatively impact north-south passage during wetter seasons but dries to mostly sub-surface flow during the rainless summer. The paths along the creek are almost exclusively rounded stones rubbed smooth by water action. With regards to vegetation, the openings to the bridge are largely clear apart from sparse trees. The most recent recorded data for these cameras were taken on 4/20/2015, jointly representing 869 days of service, and these camera remains in place as of this writing.

Culvert

Two Bushnell Model 119476 cameras are located on either end of this culvert that were installed on 6/10/2013, but were moved to a closer, Telespar-mount on 9/23/2014 in order to get a better perspective on wildlife use of the culvert. This culvert is approximately 5 feet wide, 5 feet high, and 40 feet long. No water is found on either end of this culvert and it remains dry year-round. As there is no likely route for water to pass through this structure, the original purpose of its installation is uncertain though it was likely installed so that livestock could pass safely under the highway. There is no major vegetation coverage at the entrances of this culvert. The most recent recorded data for these cameras were taken on 4/20/2015, jointly representing 680 days of service, and these camera remains in place as of this writing.

Data Collection

Deployed cameras were visited every four weeks for servicing and maintenance. Service included replacing all batteries in each camera with a fresh set of 12 AA batteries or 6 C batteries, depending on the model of camera, and exchanging empty memory cards for the ones holding data within the cameras. During servicing, cameras were checked to ensure that trigger settings remained accurate, a step that was especially important with the Bushnell cameras as the date and time on the camera had a tendency to reset to 0:00, 1/1/2012 when the memory cards were changed. In the event that the number of images taken by a camera was clearly influenced by an environmental factor (like waving vegetation), usually intuited by the number of recorded images exceeding 1,000 over the previous month, steps were taken to clear the field of view. This was usually accomplished by cutting down nearby vegetation with a machete, though in some instances the camera's location or angle needed to be shifted. Cameras were also maintained during these visits with meticulous records being kept of the dates and types of malfunctions. Cameras that malfunctioned multiple times were replaced.

There was also an issue with members of the general public "interacting" with the cameras. On several occasions, pedestrians who noticed the cameras apparently attempted to tamper with the installations. In all occasions save one, the metal housing of the cameras proved sufficient to protect the cameras from damage or theft. On October

10, 2014 one individual committed an act of vandalism and stole 9 cameras from a study site near North Bend, WA. This resulted in a removal of the remaining cameras in that region and a redesign of the protective housing used for the cameras. The results of this process included thicker metal housing for the cameras, welding of brackets to the Telespar mounting posts, and locating cameras in places where they would not be as easily visible to passersby.

When cards with data were returned to the Olympia WSDOT office, they were processed by visual interpretation of detections. Relevant information was recorded for each detection including: date, temperature, start time of the detection (in Pacific Standard Time), end time of the detection (in Pacific Standard Time), species, age, gender (if identifiable), total individual count, and a determination as to whether the observed animal passed through the relevant structure (Sullivan, 2014). In the event of multiple individuals of any species in a single detection, a single record was made, but the counts for species, age, etc. included all individuals within that record. Species determinations were carried to the species level whenever possible though due to poor image quality or camera angle, some observations proved unidentifiable, especially smaller mammals. Data were organized onto a series of Excel spreadsheets that were updated monthly.

Data Processing & Statistical Analysis

Running spreadsheets were maintained for each camera that were updated each month as new images were collected on the data cards. These spreadsheets were then merged into a single running spreadsheet for each structure. In most cases, multiple cameras were in place on a structure, to help confirm passage or to cover the larger spaces beneath bridges. Where there were multiple cameras on a single structure, observations were combined from all relevant sources with duplicate observations being excluded. A notation was also made in the structure-level spreadsheet whether the observed individual successfully crossed the structure based on the multiple angles and sides under camera coverage.

From the deployment of the first camera selected for this study until the end of data collection for this study, a total of 36,896 individuals were recorded in 11,839 detections over a period of 5,538 concurrent (1,209 sequential) days of observation. For the purposes of data analysis, the observations from each structure were limited to the most current complete annual cycle. This retained 18,702 individuals observed during 5,671 detections. It should be noted that the majority of these, 15,038, were humans and related species. As some camera have been decommissioned and others had period of malfunction where a month of data was lost, the dates of these annual cycles are not necessarily the same. In the cases of the Cascades Wet and Dry Culverts, a full annual cycle was not available with 357 days' worth of data collected for the former and 299 days' worth for the latter. To correct for the temporal disparity, observation and passage rates were calculated as weekly rates.

Once observations were identified down to the lowest taxonomic level (typically to species), a total of 33 different animal types had been recorded, from Wild Turkey (*Meleagris gallopavo*) to cougars to pika (*Ochotona princeps*). As this number was seen as unwieldy for comparison of passage communities across structures, all observed species were summarized into one of 6 animal type groups with presumed similar distinct behavioral traits and habitat requirements: Human (including domesticated canines and horses), Ungulate (hooved mammals), Large Carnivore Mammals, Small Carnivore Mammals, Small Prey Mammals, and Birds. Once summarized thusly, pie charts were constructed for each studied structure to visually interpret the differing compositions of use communities.

As much of this study is observational in nature, statistical analysis is not present omnipresent. When discussing how animal use of paired structures differed or how movement of small mammals changes with the introduction of elevated paths, descriptive text and visual observations are noted rather than statistical methodology. For the remaining sections, where statistical analyses were necessary, a combination of JMP, R, and Resampling Statistics for Excel were used. As seen in the following results, regression, analysis of variance (ANOVA), and Pearson's chi-square tests were performed when relevant to the variables.

Results

Passage Structure Styles and Elements

The data collected from the suite of deployed wildlife cameras over a single calendar year revealed several distinct patterns of human and wildlife presence that can be partially attributed to the dimensions, type, and form of the structures studied (Table 1).

Bridges vs Culverts

When performing an analysis of structure use by structure type, two of the nine sites were excluded: Cascades Wet Culvert and Western Forest Trail 1. Cascades Wet Culvert was excluded due to a number of confounding variables present at that site but not others, most importantly the sizeable flow of water through the structure without any dry passage possible. This factor resulted in extremely little use of the structure by either human or animal populations. Western Forest Trail 1 was excluded as a major dataset outlier. As Western Forest Trail 1 covers a popular running trail, mean human use stood at 135.5 individuals per week; the remaining structures all operated within a range of 0.5 – 4.1 individuals per week.

In an analysis comparing mean weekly observation rates for wildlife by structure, no significant difference was found, though there may be a slightly higher rate near bridges where wildlife were observed at a rate of 11.29 individuals per week per structure as contrasted to the 8.19 individuals per week seen on average at culverts ($p = 0.5067$). When the same analysis was performed for human observations by structure, there was again no significant difference found with both structure types exhibiting an observation rate of approximately 1.8 individuals per week per structure, though the number of observations of researchers (sometimes at a rate as high as 1 per week) combined with the relatively low totals overall likely diluted any potential preference ($p = 0.9535$) (Figure 6).

When the confirmed crossing rates were instead analyzed, however, more telling information was apparent. A One-way ANOVA of percentages of confirmed crossings by all individuals out of the total observations bordered on statistical significance with human and wildlife apparently crossing at a higher percentage of observations through bridges rather than through culverts ($p = 0.0527$). When the data was limited to only wildlife observations for the analysis, there was an even stronger pattern showing significantly higher confirmed crossing rates for wildlife through open bridge underpasses, at 67.2% of total observations, rather than narrow culverts, at 26.9% of total observations ($p = 0.0216$) (Figure 7). It should be noted that bird observations were included in the observation analysis, but not the crossing rate analysis due to the difficulty inherent in judging movement routes of birds via still-frame images.

Dimensions and Environment

Neither structure cross-sectional area nor length proved significant predictors of usage patterns. A bivariate fit of wildlife individuals per week and confirmed passage percentage by passage length resulted in insignificant relationships ($p = 0.7234$ & $p = 0.3345$, respectively). The fit does seem to indicate the possibility that increased passage length decreased confirmed crossing rates, however.

A bivariate fit of successful passage percentage by cross-sectional area also showed no significant relationship, though the line of best fit did show a positive slope indicating some likelihood that passage rates may improve with larger cross-sectional areas ($p = 0.4918$). A binomial fit of wildlife individuals per week by cross-sectional area demonstrated the strongest relationship, but it was again not statistically significant ($p = 0.1590$). This binomial fit showed an increase in wildlife observations as cross-sectional area approached approximately 200 m^2 before decreasing with areas greater than that (Figure 8).

Many studies suggest that an “openness ratio,” defined as cross-sectional area divided by length, is an important determinant of use by mammals, especially larger and medium-sized ones (Cain et al., 2003; Jacobson, 2002). Using this metric in place of cross-section alone to predict wildlife activity offered mixed results in this study. The binomial fit of number of individuals observed per week versus openness ratio offered a marginally worse fit than cross-section ($p = 0.1618$). The bivariate linear fit of successful crossing rate for wildlife showed a marginally better fit than cross-section ($p = 0.4886$) (Figure 9).

One structure from this study, specifically the double box Cascades Wet Culvert, is notable for the presence of a continuous stream running through. No other observed culvert has more than an occasional trickle of rainwater or snow melt and the bridges observed either were dry as well or were wide enough to accommodate dry passages on either side of the spanned river. It is notable, therefore, that the Cascades Wet Culvert structure represented the lowest passage totals and rates of any structure. In the 357 days that this culvert was under the view of a motion-triggered camera, every one of the 27 human observations was attributed to researchers servicing the camera on a monthly basis. The remaining 17 wildlife sightings resulted in only 2 confirmed crossings, both numbers representing a use profile far lower than any other structure (Table 1). Of the paired square cement culverts, both confirmed crossings occurred through the western option, which carries significantly less water than the eastern tunnel.

Structure Elements

As previously discussed, smaller wildlife have a tendency to pass along elevated structures when the option is available. While none of the structures from this study were equipped with wildlife shelving (whether such a structure even exists in Washington State is unknown), anecdotal evidence from these cameras would seem to support this supposition. Upon installation of the first cameras at the Cascades Dry Culvert East on

June 19, 2014, it was observed that many of the animals that approached the structure made use of a fallen tree branch on the southern end that ran towards the entrance. In the case of species like Douglas squirrels and deer mice, this proportion was particularly large. During the 11/10/2015 and 3/9/2015 services, further tree branches were moved towards the entrances of the structure on both the northern and southern ends of the structure to see how wildlife would respond. The reaction was nearly instantaneous as rodents passing through the culvert began to make virtually exclusive use of the branches to transit to and from the entrances (Figure 10). The branch placed on the southern entrance, however, had a unique use pattern as animals approaching the culvert from the south made use of the branch, but stopped at the end as, unlike the northern branch, the southern branch stopped just shy of the actual tunnel. In some cases animals spent full minutes perched on the end of the branch and moving back and forth in apparent indecision or confusion before electing to enter the structure without using the branch (Figure 11).

Species Diversity in Passage Structures

Of the 16,744 individuals recorded as having passed through one of the observed structures during the one-year periods that the data were parsed to, 16,698 were identified down the species level, revealing a complex and interrelated passage community that perhaps outstrips the general perception in terms of diversity. The vast majority of these individual crossings, 14,920, were identified as human, canine, and horses. In total, 33 species were identified as having approached one of the 9 passage structures observed, and 26 species could be confirmed as having had at least one individual successfully cross through. The combined passage rate for all observed individuals was 89.53%, though that rate dropped to 49.78% when the human subsection was excluded (Table 2).

Confirmed Passage Percentages

A number of details became apparent as data were collected about species-specific crossings, especially a number of striking disparities in confirmation rates. First, the highest passage rate by summarized species type was a perfect 100% by large carnivore mammals, but this was the result of only 5 observations between all cameras, all of a single cougar individual on multiple occasions at the Eastern Dry Forest location. After this population came humans and related species like domestic canines and horses at a 99.22% success rate, though it should be noted that when canines were observed near structures absent humans, their success rate fell to 57.14% (Table 2).

Ungulates passed through available structures at a 56.38% rate, but this does not fully reveal the disparity in this collection as black-tailed deer successfully crossed at a 73.18% rate, far higher than the 47.54% rate for the larger elk species. This divergence in confirmed passage rates was analyzed using a chi-square test and found to be of a high statistical significance ($p < 0.005$). No successful passages were recorded for cattle, but the only cattle observed were caught by one of the Cascades River Valley cameras that could see into a neighboring fenced-in cattle field that cattle could not enter from (Table 2). Cattle accounted for less than 2% of the total ungulate observations, but when they were excluded, successful passage rate rose to 57.74%.

Small carnivorous mammals achieved a 68.75% success rate as 88 of the 128 observed individuals made use of these structures for transit. Bobcats were the most commonly observed species of carnivore, accounting for almost 40% of the total and crossed structures at a higher-than-average rate of 93.75%. Coyotes represent something of a trend in that they are again a larger species within a subset that show a much smaller chance of successful transit, with only 13.64% of the observations being confirmed successes (Table 2). A chi-square test comparing the passage rates between bobcats and coyotes, again similar to the deer/elk relationship, showed a strong statistical difference ($p < 0.005$).

Small prey mammals proved difficult to identify at times due to their small size, speed, and generally nocturnal active periods, which combined to produce blurred pictures on many occasions. For these reasons, a relatively high number of small prey mammals remained unidentified in terms of species, 234 of the 799 whole. Of those that could be identified, Douglas squirrels, at 144, bushy-tailed woodrats, at 136, and deer mice, at 213, comprised most of the population counts. Contrary to the pattern established with ungulates and small carnivore mammals, with small prey animals the larger species passed at a higher rate with snowshoe hares, Douglas squirrels, and bushy-tailed woodrats succeeding 68.42%, 64.58%, and 42.65% of the time, respectively. Conversely, smaller species like deer mice and Townsend's chipmunks crossed at lower rates, 18.31% and 18.18%, respectively (Table 2).

Birds were not a group specifically targeted by this study, but their relative abundance near passage structures merited their inclusion in this data analysis. In fact, nearly twice as many birds were observed by these mostly low-angled, close-view cameras as small carnivore mammals. Ninety-five of the 203 observed birds were identified as American Robins, 37 were Varied Thrushes, 20 were Steller's Jays, and 14 were Wild Turkeys; these represented the major populations observed. As the movement patterns of birds, namely long periods of being stationary before a sudden burst of quick motion resulting in the vacating of an area, is unsuited for the motion-triggered cameras used, very few confirmed passages could be accounted for, resulting in a success rate of 7.39%. The actual number may, in fact, be higher, but this study was not designed to account for bird movements and thus can only confidently discuss bird observations, not crossings other than to note that all confirmed passages took place beneath bridges and the only species that could routinely be confirmed as crossing beneath were the larger, slower, ground-dwelling Wild Turkeys (Table 2).

Paired Structure Analysis

Except for the Cascades Wet Culvert, where the structures were close enough that they cannot reasonably be considered independent from one another, every structure in this study had a paired structure in a similar, nearby location, but with each matching structure possessing one targeted difference. A number of differences, including dimensions, vegetation coverage, and camera coverage existed between these paired structures, but each pairing also had one of the several large disparities here described that could influence use communities.

As noted before, the Cascades Wet Culver was mostly filled by water throughout the year. This had a major effect on the crossing community in that it effectively ensured that none existed. In fact, the presence of researchers servicing the camera accounted for nearly 2/3 of the total observations. Of the perceived animals, all were small and generally uninterested in passage (Figure 12).

The paired Cascades Wet Culverts differed in size and human pedestrian use. The western culvert had a cross section of 3.53 m^2 and saw 174 humans make use of it throughout the study period in contrast to the eastern culvert, which had a cross section of 1.13 m^2 and only recorded 23 human uses, most of which were attributed to the camera operators. These differences had very little impact on small carnivore use, but the number of small prey animals was more than four times higher in the smaller, more secluded eastern culvert where they made up more than 3/4 of the entire population (Figure 12).

The Western Forest Trail structures were, in fact, the same bridge, but on either side of a major river, dike embankments, and fencing. The communities could thus reasonably be considered separated, with the eastern trail having much higher human use. With nearly 15,000 humans passing through the eastern structure over the study's span, wildlife presence was excluded almost entirely (46 observations), but on the western side of the river, ungulates moved with relative ease as they represented the vast majority of observations at 377 of the total of 421 (Figure 12).

The Cascades River Valley Main Bridge and Overflow Bridge differed in that Main Bridge spanned a river while the overflow bridge had a dry underpass. This resulted in higher human presence (202 individuals) beneath Main Bridge, mostly fishers and recreational swimmers, and much lower ungulate use. Despite only being located only a few hundred feet down road from Main Bridge, Overflow Bridge had more than three times more ungulate observations, 1,015 versus 324, in part likely due to the significant decrease in human use, down to 55 individuals (Figure 12).

A bridge and culvert were selected on for the East Dry Forest site due to their close proximity, but clear structural dissimilarity. This pairing resulted in much more biodiversity near the culvert as small carnivore mammals, small prey mammals, and birds accounted for 42.5% of the observations where they were only identified in 3.7% of the bridge observations. It must be noted that the cameras installed observing the bridge were not installed with a design intended for observing small animals, but with four overlapping cameras that have shown a capability to capture animals as small as bobcats, canines, and California ground squirrels on occasions, the disparity remains suggestive. In addition, the larger cross-sectional area East Dry Forest Bridge contributed to the counting of nearly five times as many ungulates as the smaller culvert (628 versus 131 individuals) (Figure 12).

Human Impact on Wildlife Passage

Human and Wildlife Use Rates

A bivariate linear fit of mean weekly human observations by mean weekly wildlife observations resulted in a highly suggestive negative relationship that is significant at the $p = 0.1$ level, but not at the $p = 0.05$ level ($p = 0.092$) (Figure 13). For this correlation analysis, the Cascades Wet Culvert site was excluded due to its environmental confounding variables and the Western Forest Trail 1 site was excluded due to its extraordinarily high human use rate overwhelming the dataset.

When observing the dispersion of the data, there appeared to be a natural division in the dataset once human observation rates reached approximately 3 individuals per week. Performing a One-way ANOVA by dividing human observation rates into categorical variables of >3 or <3 individuals per week resulted in a significant decrease in wildlife observation rates in the >3 per week categorical ($p = 0.016$) (Figure 14). This categorical analysis style also allowed for the reintroduction of the Western Forest Trail 1 site to the dataset as the high human use did not shift the entire graph. This evidence would support previous studies that argued that a low level of human use of underpasses has little impact on wildlife use, but once human use reaches a certain level, there is a significant direct impact.

Human Impact on Wildlife of Different Sizes

A question arose during this analysis as to whether human activity had a different impact on larger animals when compared to their impact on smaller animals. A bivariate fit analysis of number of large wildlife individuals per week (including the Ungulate and Large Carnivore Mammals subsets) by the number of observed human individuals per week showed no confirmed statistical correlation, but did suggest a slope of -0.98 large wildlife individuals/human individual ($p = 0.6516$) (Figure 15). A bivariate fit analysis of number of small wildlife individuals per week (including Small Carnivore Mammals, Small Prey Mammals, and Birds) by the number of observed human individuals per week also showed no confirmed statistical correlation, but had a slope of -0.83 small wildlife individuals/human individual ($p = 0.5527$) (Figure 15).

While this analysis would seem to indicate no real difference in human impact on wildlife species of different sizes, a number of confounding variables limit the utility of the results. Specifically, though this analysis again excluded Cascades Wet Culvert and Western Forest Trail 1 as outliers, human observation rates were much higher around bridges, where larger mammals operated almost exclusively. Also approximately 0.5 human observations per week were due to camera servicings by researchers, unduly influencing sites with low human use.

Human and Wildlife Co-use of Structures

An ANOVA of wildlife observations by structure type showed that, in summary, wildlife approach bridges and culverts at equal rates, with virtually no difference in individuals per week between the types ($p = 0.968$). An ANOVA analyzing the same distinction among humans again showed no significant difference as well, though a slight preference for bridges appears largely as a result of the inclusion of the Eastern Forest Trail 1 site ($p = 0.394$). This analysis shows that both types of structure are important for wildlife passage and human passage, though bridges may be slightly more important for humans.

Discussion

Overall, the findings from this study show that transportation structures like culverts and bridge underpasses provide passage potential for different use communities based on a number of factors like structure type, cross-sectional area, water presence, and human use rate. In particular, this research provides novel information of the number and variety of small animals that commonly make use of culverts and bridge underpasses in western Washington and suggests how environmental and architectural factors can influence these use communities. Based on patterns observed by camera traps placed around multiple structures located near to one another, inferences can be drawn about what known differences account for these differences. The observational nature of this study precludes the ability to categorically state what structural or environmental elements definitively affect wildlife crossing rates either positively or negatively, but differences in observed populations have proven highly suggestive.

This research presents the determination that the small (<50 lb.) wildlife species that make use of passage structure, especially smaller culverts, do so at a high rate and with a great deal of species diversity. In addition, wildlife presence and confirmed crossing rates generally increase with the increased cross-sectional area presented by bridge underpasses. Low levels of human pedestrian use seem to have a minor effect on wildlife use, but increased use results in an apparent, though not statistically significant at the $p < 0.05$ level, decrease in wildlife use. Finally, small wildlife use of downed tree branches to enter and exit passage structures, especially ones that actually enter said structure, would suggest that they prefer to move through culverts above ground level when the option is available.

Passage Structure Styles and Elements

One site, more than any of the others, seemed to have its use community heavily defined by certain environmental and structural factors in place. Specifically, Cascades Wet Culvert was the only site of the 9 selected that did not have a dry passage route available for most of the year as well as being the only double culvert and the only culvert constructed out of concrete instead of corrugated metal. Consequently, when observations of researchers servicing the cameras are excluded, use of the Cascades Wet Culvert was minimal, less than 10% of the total of the next-least-used structure. This aversion for small wildlife to make use of a culvert with permanent flowing water fits with the expectations of the research given existing literature on the subject (Serronha et al., 2013). Even among the culverts studied, which generally exhibited lower use rates than the bridge underpasses, the Cascades Wet Culvert proved a major statistical outlier. Given the apparent unsuitability of this structure for wildlife use, it is interesting that the confirmed crossing rate (14.3%), while still less than the remaining culverts, is not terribly out-of-line with their rates, which were calculated to be as low as 18.9%. How much of this is due to the small sample size at this structure, numbering a mere 14 non-bird wildlife individuals, and how much is due to willingness for small wildlife to use typically-unsuitable passage structures when no other option is readily available is up to interpretation. The bridge cameras, specifically those on the Western Forest Trail and East Dry Forest bridges that spanned streams did occasionally observe ungulates moving fairly easily through significant water features, but the small body size of the typical animals that make use of culverts does not lend those individuals to movement along anything but dry paths (Wolff & Guthrie, 1985).

The culverts in general recorded fewer observations when camera operator detections are excluded than the bridge underpasses, with an average of 320.25 individuals seen per culvert and an average of 3,420.8 individuals seen per bridge underpass. Each structure type included a major dataset outlier, however. As noted, Cascades Wet Culvert proved to have nominal use compared to other culverts, but Western Forest Trail 1 exhibited the opposite extreme, recording almost 14 times as many individuals as any other bridge. When those low and high extremities are excluded from the dataset, the numbers of individuals recorded per structure type prove to be more similar, with 418.33 detected per culvert and 675.5 detected per bridge. Restricted entirely to wildlife, thus excluding the human and related species observations, the difference in observations indicate a similar relationship, with 492.8 individuals seen per bridge and 278.5 per culvert. The difference remains sizeable, but no longer seems so overwhelming. The values for each individual structure varied widely within type groups; however, different bridges saw between 46 and 1,029 wildlife individuals over the annual cycle while different culverts had observations that ranged from 17 to 636 individual animals. This lack of any semblance of homogeneity within structural design datasets suggests that a number of factors play a role in determining animal use beyond simply the type of structure.

One such factor could be the cross-sectional area or openness ratio (cross-sectional area/length) of the passage. This study showed that the number of observations generally increased as cross-sectional area increased before levelling off around 100-200 m^2. Although the data also showed an apparent decline in observations per structure past that apex, the limited camera coverage for larger structures with the camera resources available is likely the primary cause. It would not be expected for wildlife to show a negative selection pressure against structures that offer more open passage space. Instead, the fact that larger structures dictate that cameras be placed further back, combined with the limited range on the triggering mechanisms for the cameras used for this study, meant that an unknown number of animals likely made use of these larger structures without any record being made available.

In addition to cameras located near bridge underpasses identifying higher numbers of individuals than those on culverts, the bridge cameras also showed a much higher confirmed crossing rate for humans and wildlife as many individuals that approached culverts elected not to pass through them. When both populations were combined, the passage rate for bridges was approximately 75% compared to approximately 35% for culverts. The disparity is even more apparent when wildlife (excluding birds) were analyzed independent of the human population, with a confirmed crossing rate of about 75% for bridges and about 20% for culverts. Birds were excluded from confirmed crossing rate analysis due to the ineffectiveness of motion-triggered still-frame cameras in determining bird movement paths. These findings, that large, open spaces beneath bridges offer a variety of habitats and movement paths that are most conducive to animal use, support other research findings (Connolly-Newman et al., 2013; McCollister & van Manen, 2010).

Current scientific knowledge states that small mammal populations will voluntarily move along branches or other physical elements rather than on the ground when the option is available and anecdotal evidence from this study supports this perception (Foresman, 2004). The Cascades Dry Culvert East is surrounded by a fair bit of debris from fallen tree branches due to the thick mountain forest in which it is located. After initial deployment of cameras on this structure, it was observed that the majority of the small wildlife observed, especially Douglas squirrels and deer mice consistently moved back and forth across one of these downed branches that happened to be in front of one of the cameras. As this particular branch was not contiguous with the culvert, but merely in the vicinity, researchers grew curious about whether this behavioral pattern would change when the elements were combined. Starting with the north end of the culvert, where smaller mammals tended to pass closely along the western wall of the culvert and medium sized mammals (mostly bobcats) generally moved down the center, a nearby branch was placed along the eastern wall of the culvert so as to minimally impact traditional movement paths. After a few initial days that the individuals in this community required to acclimate to the new element of the culvert entry, the apparent preference for small mammals to use branches to move across the ground replicated with the new branch was completely replicated. In fact, wildlife grew so accustomed to the branch leading into the culvert that individuals from a number of other small mammal species began to make nearly exclusive use of the branch to enter and exit the structure, shifting their movement path from the western wall to the eastern wall so as to take advantage of the elevated path. Though this represents a sample size of one and is absent a control and the other mechanisms to ensure that no false pattern is perceived through imperfect design, the near-immediate overwhelming reaction of these species to switch which side of the culvert to move on so as to instead walk along the branch is certainly interesting and suggests further study is warranted.

Following this relatively successful exercise in ad hoc habitat alteration, the process was repeated with the southern entrance to this culvert. Again a nearby downed tree branch was pressed into service to serve as a natural elevated pathway leading into the Cascades Dry Culvert East. The branch was again placed along the eastern wall of the culvert both to keep the pathway clear for easy passage and to observe whether small mammals would voluntarily abandon their normal movement route along the western wall to instead use the branch. The difference in researcher action in this scenario was that the branch was placed so that it ended just before the entrance of the culvert, whereas the branch on the northern end extended approximately two feet into the mouth of the structure. This again provided for interesting observational data about small mammal movement. While these animals again, once acclimated, grew to make use of the branch almost exclusively, the majority hesitated upon reaching the end of the branch before turning around, leaving the branch, and entering the structure along the traditional western wall. Wildlife leaving the culvert often made use of the branch, but not to the same extent as the northern of the pair. These exercises suggest that elevated pathways are particularly preferable for small animal movement regimes, but offer the impression that it is important that any potential elevated pathway should extend at least some distance into the passage structure or, ideally, provide an elevated pathway through the entire length of the structure to best maximize usage.

Species Diversity in Passage Structures

A total of 26 independent species were confirmed as having crossed completely through one of the observed passage structures as part of this study. These species were divided up into one of 6 different population groups that could be assumed as having roughly similar habitat needs and behavior traits: human & related, ungulate, large carnivore mammal, small carnivore mammal, small non-carnivore (or prey) mammal, and bird.

The first category, human & related, was primarily composed of humans, but included two species that, in most cases, only made use of passage structure while accompanied by humans: horses and domestic canines. Seven of the 9 structures exhibited human use beyond that attributed to the camera operators; only two of the three smallest structures, Cascades Wet Culvert and Cascades Dry Culvert East had absolute wildlife use. That humans made use of so many of these structures to cross roadways despite access limitations due to environmental factors like thick forest or locations relatively isolated from human settlement speaks to the idea that excluding human use in the interests of promoting wildlife use is often not a viable option. Proportionally, human use of these structures seems to impact some species types more than others. For the Cascades Dry Culverts, for example, humans accounted for 3.5% of the detections for the eastern culvert with small prey mammals representing 76.3% of the detections. In the western culvert, the percentage increase of human use to 46.3% came largely at the expense of small prey mammals, which dropped proportionally to 31.1%. The percentages of the use communities composed of small carnivore mammals and birds remained approximately the same for the two culverts at about 6% and 15%, respectively. This is likely the result of a temporal divergence in use patterns. Whereas birds were largely observed near dawn and small carnivore mammals were primarily seen late at night, human hikers were mostly recorded from the late morning until dusk. While this temporal human pattern likely did not affect nocturnal prey species like bushy-tailed woodrats, it seems likely that the other major small prey mammals located in this region were affected. Townsend's chipmunks, Douglas squirrels, and deer mice, which are active during the day or near dusk, were possibly discouraged from approaching the west culvert due to increased human presence, shifting the proportions of the use community.

Ungulates, as should be expected, primarily made use of the bridges studied here rather than the culverts due the size constraints of the latter. There seemed to be a fairly clear inverse relationship between human observations and ungulate observations at paired structures where an increase in the former would result in a decrease of the latter. Ungulates appear to have very particular requirements when the decision arises as to whether to actually make use of a passage structure once approaching it. The Cascade River Valley Main Bridge and Overflow Bridge offer a perfect example of this behavior.

Ungulates here followed the pattern of inverse observations with ungulates composing 59.1% of the use community on the Main Bridge and 93.6% of the use community beneath the Overflow Bridge where humans composed 36.9% and 5.1% of the same respective structures. However, the passage rates did not mirror this relationship. Ungulates (excluding cattle that were precluded from passage by nearby pasture fencing) crossed the Main Bridge successfully in 71.9% cases, but only did so in 18.1% of cases for the Overflow Bridge. This reinforces the fact that a number of factors play into an ungulate's decision on whether to use a passage structure. In this case, the Main Bridge was significantly larger than the Overflow Bridge (420 m^2 cross-section vs 168 m^2 cross-section) and the vegetation around and beneath the Main Bridge was preferable for ungulate feeding. The blackberries and tree shoots that were allowed to freely grow were more attractive to ungulates in this region than the grasses around the Overflow Bridge that were routinely cut as a part of regular maintenance. Ungulates in this area found easy grazing pasture near the Main Bridge and likely crossed it in search of more, but eschewed the Overflow Bridge as a route of travel due to these limitations.

Large carnivore mammals made up a very small portion of the overall samples, with a single individual cougar being sighted on five occasions at the East Dry Forest Bridge. Four of these 5 sightings occurred during daytime, seemingly belying the notion that large carnivore mammals shift their use patterns to be more nocturnal when a structure has a substantial human presence (Rodriguez, Crema, & Delibes, 1996). It should be noted, however, that this cougar has been observed by other WSDOT cameras in the region moving throughout the area at night on more occasions that don't fit in with this dataset. The fact that this cougar elected to make use of the East Dry Forest Bridge on all 5 of these occasions, but never approached the nearby East Dry Forest Culvert despite existing research suggesting that cougars prefer more confined structures is also somewhat unexpected (Clevenger & Waltho, 2005). This could be because one end of that culvert is located in fairly dense forest land, while research indicates cougars prefer clear and open entrances, which is provided by the bridge here (Clevenger & Waltho, 2005). Large carnivores have been seen at some of these sites prior to the window of time that the data was limited to here for analysis and at other WSDOT sites under observation as part of the Habitat Connectivity program, especially black bears. The black bears in these sightings have passed through structures of various sizes and at all times of day, suggesting that large carnivore mammals may be less restrictive in their use requirements than expected. It was unanticipated, given prior knowledge of how black bears use these structures in Washington, that no individuals were observed at any of these sites within the annual cycle despite all being located in potential black bear habitat.

Bobcats accounted for more than half of the small carnivore mammals that this study identified and could be confirmed as having successfully crossed through structures at a very high rate of 93.75%. This was a behavior that was exhibited by all small carnivore mammal species except coyotes, which crossed in 13.64% of observations, the only group within this subset to do so less than 54% of the time. This difference is probably best explained by the size and behavior differences. Coyotes stand several inches taller at the shoulder and weigh about 10 pounds more on average and a number of observations of coyotes approaching smaller culverts, such as that at Cascades Dry Culvert East, showed coyotes approaching the structure before turning and walking away. While these culverts could easily pass a smaller bobcat through comfortably, a coyote would have found a somewhat more constricted route. It is possible that feeding habits may play a role in this as well. While both species can hunt live prey and scavenge the kills of other animals, bobcats are primarily hunters while coyotes are the more likely pf the two species to feed on carrion (Whitaker & Hamilton, 1998). On at least three occasions, bobcats could be identified in the collected images as having passed one way through a passage structure before returning later from the opposite site carrying freshly-killed prey. It may be that bobcats recognize the importance that culverts and underpasses play in maintaining connected hunting ranges and have thus see passage as a necessity while coyotes, absent the same reliance on hunting practices to satiate hunger, lack this incentive. Any number of other possible reasons for this disparity may exist, such as proximity to dens or coyotes may be more resistant to the noise, light, and movement from traffic and thus be more willing to cross at grade.

It is difficult to interpret structure type preference for some of the smaller animals appearing in this study such as the small prey mammal group. Because of limited resources, bridges in this study had between 2 and 4 cameras each and, because they had to cover a relatively large area, were necessarily placed further back from the structures and higher above the ground than the cameras placed on culvert. This methodological requirement did not prove conducive to gathering the best understanding of total use rates by small prey mammals for bridge underpasses. Of the bridges observed, the most likely to capture small prey mammal movements would be the Eastern Dry Forest Bridge, which had 4 separate cameras in place, or the Cascades River Valley Main and Overflow Bridges, which each had a camera placed near ground level directly beneath the overpass. Small prey mammals were observed, however, making use of all 4 culverts and 1 of the 5 bridges in this study, with that one being the Eastern Dry Forest Bridge. Though it is difficult to confidently describe small prey mammal use of bridges, it was expected that they would contribute more to the biodiversity in use communities for culverts and the available data does support that supposition. Small prey mammals compromise at least 29.5% of the observed individuals in each of the culverts studied where the close confines, darkness, and ready access to nearby screening vegetation at the entrances and exits would suit their habitat needs. The wide open, mostly rocky bridge underpasses would leave these animals vulnerable to predation. The relatively high number of individuals that remain listed as unknown in this study's data tables is primarily the result of the initial cameras deployed at the Cascades Dry Culverts being older model Bushnells incapable of providing a clear image of rapid small mammalian movement at night; identification rates increased when these sites were resupplied with Reconyx cameras instead, but that was a relatively recent development in the terms of the timescale of this project.

Birds had a higher-than-expected presence in these sites. A wide variety of birds were identified, from perching birds like the Varied Thrush and American Robin to ground-dwelling birds like Wild Turkey and Ruffed Grouse to a ground foraging woodpecker, the Northern Flicker. As the cameras used for this study take still images, they are not adequate for determining whether birds successfully crossed through structures in most cases, so the low subset crossing rate of 7.39% is likely not representative of actual behavior. All of the birds that could be confirmed as having crossed, however, did so through bridge underpasses as, despite a high number of observed individuals resting near and even in culvert entrances, no confirmed passings proved recordable. The primary species of bird that did cross at a relatively high rate of 42.86% was the Wild Turkey, which is understandable given that the species spends most of its time on the ground. Recent research in Montana suggests that regular passage of birds along the ground beneath underpasses may not necessarily be reserved for ground-dwelling birds, however. Hundreds of sage grouse, a species known as strong flyers, have been recorded as walking beneath underpasses each year in that state (Peterson, 2014).

Human Impact on Wildlife Passage

Human use was observed in 7 of the 9 structures observed outside of camera operator contacts. The results showed a negative relationship between increased human presence and the number of wildlife individuals observed. This supports existing knowledge on the relationship between these two populations (Pedevillano & Gerald Wright, 1987). This data was not equally distributed or completely linear, however, with a clear break in results once the number of human observations per week reached between 2-3. The structures with human presences below this threshold averaged about 14 wildlife individuals per week while those structures with human presences above that number averaged less than half as many wildlife observations per week. This result, suggesting that the negative impact of human use on these structures does not increase linearly, but has a flat effect at low and high levels, with an exponential growth in impact in between, is also supported by current literature (Mata et al., 2008).

Western Forest Trail 1 served as an extreme example of how human activity can make the habitat unsuitable for wildlife passage. With 14,383 humans and related species seen at this site during the annual cycle of data collected, wildlife were largely excluded from use, with only 46 individuals being identified. On the opposite end of the spectrum of human impact, Cascades Wet Culvert and Cascades Dry Culvert East both saw only researcher use of the structures by humans. It is notable that statistical analysis of the results showed that humans appear equally willing to make use of bridges or culverts, but did not do so for these two structures because they were the only structures included in this study with a clearance height below 5 ft. (1.5 m). Combined, these results suggest that so long as a structure is large enough to comfortably allow for human movement, there is a high likelihood that pedestrians will take advantage of the opportunity. This challenges the most commonly suggested method of dealing with the combined use between these disparate populations, namely the idea of merely limiting human use as much as possible. This data indicates that humans have a similar need to wildlife to pass beneath roadways and see culverts and bridge underpasses as an ideal tool for achieving this goal.

If human use is unlikely to be curtailed, but has an apparent negative bearing on wildlife use, the question remains as to what steps can best be taken to resolve the issue. This study suggests that the use of paired structures may be the best method to achieve the desired effect of uninhibited passage by both populations. As discussed in Olsson, Widén, & Larkin (2008), when multiple similar passage structures are found in relatively close proximity, human and wildlife populations will voluntarily segregate between the options. This notion bore out through the results of this study. In all of the paired structures fitting these requirements, namely relatively close proximity and same structure type (bridge vs culvert), all exhibited such a division of species. As visualized in Figure 12, human individuals heavily favored use of Western Forest Trail 1, Cascades Dry Culvert West, and Cascades River Valley Overflow Bridge while wildlife individuals similarly favored their opposite number. It would be inaccurate to state that each population made use of the structure that best suited their requirements. In reality, the human-dominated structures in this subset were all larger, more open, and easier to access, indicating that human individuals naturally made use of the structures best suited to their needs. Wildlife, in contrast, made use of smaller, less desirable structures in what may be a reaction to the high human presence at the preferable passages.

It proved interesting that increasing human use had approximately equal negative effects on large and small mammal use of passage structures. The analysis performed in this study showed roughly equivalent relationships between humans and animals of either size group, but in both cases the analysis was not statistically significant. This despite the expectation that small mammals would be more influenced by increased human use both as a result of their self-preservation instincts, more solitary nature, and the fact that larger mammals, especially ungulates, have shown an ability to acclimate to human influence (Gagnon et al., 2011). What information better fits this supposition is the fact that the baseline use rate when compared to human individuals is higher in larger mammals. The y-intercept, and thus the assumed number of observed individuals per week in the absence of any human presence, in Figure 15 shows a value more than double in large mammals versus small mammals. As a requirement of servicing cameras, researchers needed to approach these sites monthly so no site in this study could be entirely devoid of human presence. It is not unreasonable to imagine that the disparity in these y-intercept values may be even greater than that observed here if it had been possible to measure passage rates without observer influence.

Conclusions

The research performed here has reconfirmed the important role that wildlife passage structures hold in the movement regimes for animals of all sizes and suggests that a greater degree of use by small mammalian vertebrates exists than may have previously been suspected or understood. This information also supports existing knowledge of the negative influence of human presence in passage structures while recognizing that elimination of human passage is not always a viable management strategy.

In total, 33 separate species were recorded as having made use of the culverts and bridges in this study, with 26 species providing at least one instance of an individual being confirmed as having crossed through the passage. These species covered a wide variety of sizes and behavioral groups, from small and large carnivores to small and large non-carnivorous prey species. As a whole, wildlife showed a possible, though statistically insignificant, preference for bridges as a movement vector over culverts. Confirmed crossing percentage, calculated as the number of individuals who could be confirmed as having passed through the structure divided by the total number of individuals, for mammalian wildlife was much higher through bridges than culverts, indicating a likely preference for greater cross-sectional areas in passages. Observational analysis of small wildlife interaction with the elevated pathways offered by downed tree branches both near and within culverts suggests that these animals may preferentially use these paths to the exclusion of natural regimes that have been developed.

When multiple spatial close structures were analyzed together, it became apparent that human pedestrians largely confined their use to only one of the paired structures, while wildlife would mostly make use of the remaining option. Increased human use of passage structures was at least partly responsible for a consequent decrease in wildlife use of those same structures. This relationship was especially detrimental once human pedestrian observations surpassed 2-3 individuals per week, at which point wildlife use dropped precipitously. Human pedestrians made use of bridges and culverts both frequently, though appear to prefer bridge underpasses due to the increase in open area. Human influence had a similar negative linear relationship for both large and small mammalian wildlife, but larger species may be more capable of adapting to human presence than smaller species.

This study and future research can provide useful information to determine how transportation bridges and culverts, structures originally designed to traverse waterways and protect drivers from floods, are increasingly becoming important to populations beyond motorists. It is already well-established that these structures can reduce WVCs with large mammals, reducing motorist risk of injury and property damage (Clevenger & Waltho, 2005). However, as research continues into how to improve and expand the field of wildlife passage structures, it is important that unrecognized, yet sizeable, segments of the use community are acknowledged. Small animal and human pedestrian use of bridge underpasses and culverts is higher than may be predicted as these structures provide crucial pathways for safe movement for a diversity of species.

Chapter 3: Conclusions and Management Implications

<u>Conclusions</u>

Wildlife passage structures offer an important resource to all wildlife, namely freedom of daily movement and for migration between seasons or habitats. This is especially important with species of limited mobility like small animals where their smaller habitats suffer proportionally more when fragmented by roadways. This was observed as small and large carnivore mammals made regular use of underpasses and culverts in search of prey while hunting and, in the case of one bobcat individual, actually catching prey on one side of a structure before carrying the prey back to its den on the opposite end. Instead of having these animals cross roadways at grade where they are at risk of vehicle strikes as they seek to maintain their movement through a traditional range, bridges and culverts offer a valuable service in preserving habitat connectivity, population totals, and genetic diversity due to the presence of more individuals in each population and perhaps linkages between metapopulations.

Variety of structure type, size, and location is important for maintaining biodiversity in use communities. Smaller animals may prefer structures with smaller cross-sectional areas, though they were observed to pass readily through open bridge underpasses as well. Ungulates in particular seem to require very large passage structures with clear entryways and available forage vegetation. Human pedestrians also tend to favor larger structures, passing beneath bridges with some regularity while eschewing culverts with a height under 5 feet entirely among this sample set. Installation of multiple structures of varying sizes with different environmental elements seems the best method for ensuring equal access to humans and wildlife as the populations voluntarily separate and use different structures when the option is available.

Environmental factors play a large role in determining the size and composition of use communities. Permeant running water deters use by any species on a reliable basis unless dry pathways are available adjacent to the waterway. In such cases where a dry path exists, waterways may prove incidental to movement patterns or even encourage species like small prey mammals and ungulates that derive a benefit from the resultant increase in vegetation. Vegetation type also plays a role in crossing rates as in one pair of structures, ungulates crossed at a high rate though an underpass with heavy blackberry presence but crossed at a very low rate through a nearby (albeit smaller) underpass surrounded by short grasses. Elevated pathways, such as those offered by downed tree branches or installed wildlife shelving along passage walls would likely be of benefit to small prey and carnivore mammals given their apparent preference to move above the ground rather than upon it.

Management Implications

The management implications of this study are few at this junction. Much of what has been observed over an annual cycle is suggestive of practices that could be altered or improved to better account for human pedestrian and small animal use of existing or future structures, but little is conclusive. In truth, WSDOT has proven very proactive about maintaining habitat connectivity across roadways through the use of passage structures. Every year WSDOT allocates millions of dollars and employs dozens of people for the purpose of maintaining and studying the effectiveness of these structures as platforms for wildlife movement. As much of this funding is tied to reducing WVCs that endanger human motorist lives, many WSDOT projects are understandably focused on ungulate and other large mammal needs as those are the species that put motorists at the most risk. As a result, the benefits derived from small animals and human pedestrians are sometimes incidental when projects designed to pass water or large mammals beneath roadways are completed.

One potential for increased management would be the process of further segregating human and wildlife passage between paired structures. While human pedestrians commonly selected which of two possible structures offers the most preferable passage elements and gravitate towards that one, as evidenced by the data collected in this study, there can be some overspill that may decrease the utility of the second paired structure for wildlife. The solution to this may be as simple as signage. Several months after construction of paired passage structures is completed, so as to allow for movement regimes to acclimate to the new structures, camera traps could be set up to observe which of the structures humans tend to prefer. Then small signposts with arrows directing towards the structure already used by most pedestrians could potentially redirect a higher proportion of human use through a single structure, leaving the other free for wildlife use. Placement of barriers or signage designating the second structure as wildlife habitat may prove counterproductive if pedestrians voluntarily disregard such elements in search of wildlife interaction, so simple arrows may prove most effective.

The primary implication of this study is to ideally progress down an avenue of research that receives less attention than large mammal use of wildlife passage structures. The cameras deployed by WSDOT across western Washington have revealed a complex community of small vertebrates that make regular use of passage structures and a population of human pedestrians that cross through even the most isolated of locations. More needs to be known about these populations, what they look for in passage structures, what drives them away, and how underpasses, overpasses, and culverts can be designed to appeal to the parts of the use community equally. Specifically, implementation of several experimental research designs to structure evaluations such as those suggested by Rytwinski et al. (2015) could provide invaluable data.

Recommendations for Future Research

1. Continue and expand monitoring efforts and improve coverage for bridges
    a. Dataset is still too limited spatially and temporally to effectively promote management strategies
    b. Small wildlife use of bridges likely underrepresented due to difficulty in observing large underpasses so additional detection methods could be deployed
    c. Include more sites to better account for anomalous environmental factors

This study collected tens of thousands of records of humans and wildlife across 9 structures at 5 sites across western Washington, but the differences among the sites were sometimes so significant as to make categorical comparisons difficult to endorse. In addition, the cameras stationed at some sites providing the most interesting information, specifically those located near the Cascades Wet and Dry Culverts, had not yet been in service for a full annual cycle, meaning that the populations recorded at those locations were not a complete representation. The time spans were considered near enough to a full annual cycle so as not to make the results irrelevant for the purposes of this study, but as these installations remain in place for longer, the likelihood that an accurate representation of reality is being recorded increases. Cameras should be replaced with more modern, reliable cameras as time and funding allow (a policy already in place at WSDOT) as some cameras proved difficult to work with due to triggering failures or poor image quality. Finally, the deployment of more equipment around bridge underpasses, including more camera frames, track plates, and/or pitfall traps, would help in achieving a more complete understanding of small animal use of these larger structures.

2. Limit human presence (specifically camera operators) to eliminate that variable
    a. With current methodology, knowledge of structure use completely absent human presence is not possible
    b. Technological advancements offer several (expensive) options to eliminate servicing need or allow for placement further away from structures

The influence that camera operators had on sites with high human use was likely inconsequential, but at most of the sites, there was relatively little human activity. The level of impact that the passage of 1-3 individuals every 4 weeks to swap out cards and batteries on these cameras is likely not much, but remains uncertain. On at least two occasions, researchers came into direct contact with wildlife at these sites, alarming the animals and forcing them to flee. In some cases it may be possible to hard wire camera installations in place when power lines are nearby, eliminating the need to replace batteries. Some camera models also have the capability to send imagery data to computers via satellite, which would no longer require researchers to visit sites to change data cards. Alternatively, the use of larger data cards in conjunction with more electric hard wiring or more efficient battery packs could minimize the number of service trips, rather than eliminating them outright. Long distance thermal imagery cameras that would allow for cameras to be set up further back from passage structures, minimizing researcher alteration and interaction with the targeted habitat are also an option. The issue with implementation for all of these options, however, is a cost point far higher than the existing system, one that likely doesn't justify the marginal improvement in the data.

3. Designed studies with controls
    a. Observational studies such as this one are important for creating a baseline understanding, but designed studies can provide a better understanding of causal relationships and guide better management
    b. Allow for targeted testing of the role of culvert shelving, shielding vegetation, or water presence

Rytwinski et al. (2015) describe some of the many potential designed studies that can be performed with passage structures, covering a wide breadth of topics from fencing, vegetation coverage, and structure types, sizes, and numbers. Mostly these projects are designed to be applied to ungulate and large carnivore mammal concerns. With modification, any number of them could be used to observe the effects of various passage elements on small animals and human pedestrians. In addition, wildlife shelving (which is not mentioned) and water presence (which is only discussed briefly) could be major modifiers to use communities. Water flow rate, seasonality, and percent coverage seems to have a definite impact on structure preference and the observation of multiple similar sites with varying water regimes, perhaps even ones that could be modified, would provide interesting results. Foliage coverage for structure elements and wildlife shelving would prove fairly straightforward to design studies around, either by finding (or building) twin structures in the same region with one of each pair possessing shielding or shelving and the other serving as a control. Alternatively, pre-and-post installation analysis could be performed where a single structure is observed for a time, much like the ones in this study, before vegetation shielding or wildlife shelving is installed and comparing the resultant community to the baseline one.

4. Individual-level analysis for small animals
    a. Better representation of the habitat connectivity role these structures play
    b. Observe whether small animals make use of multiple structures in succession as part of normal range movement or seasonal migration
    c. Account for individuals that pass through structures on a regular basis, eliminating replication in the dataset

At many of the sites where small animals were prevalent, it seemed highly likely that a few individuals were passing through the structures multiple times. Unfortunately, without any way to define individuals through visual characteristics, there was no way to be certain of this supposition. The question also arose during research as to whether some individuals may be using multiple structure, either in series or in parallel. For instance, if a bobcat shifted its range further north, could it be tracked moving through multiple structures from south to north? Or, in a month with particularly low human presence in one of two paired structures, could an individual normally only found in the less-disturbed structure be found changing its preference? This could be accomplished through the use of pit traps to capture small animals and then using an ear or leg band or a passive integrated responder (PIT) tag. PIT tags require no sizeable power source, are easily distinguishable by one another, and can be triggered remotely by stationary installations automatically, perhaps making them ideal to this potential field of study (Gibbons & Andrews, 2004).

5. Explore the role of birds in passage structure communities
    a. Unexpectedly high numbers of birds were observed near culvert and bridge entrances
    b. Use of motion video in place of still imagery would play a major role in determining crossing rates

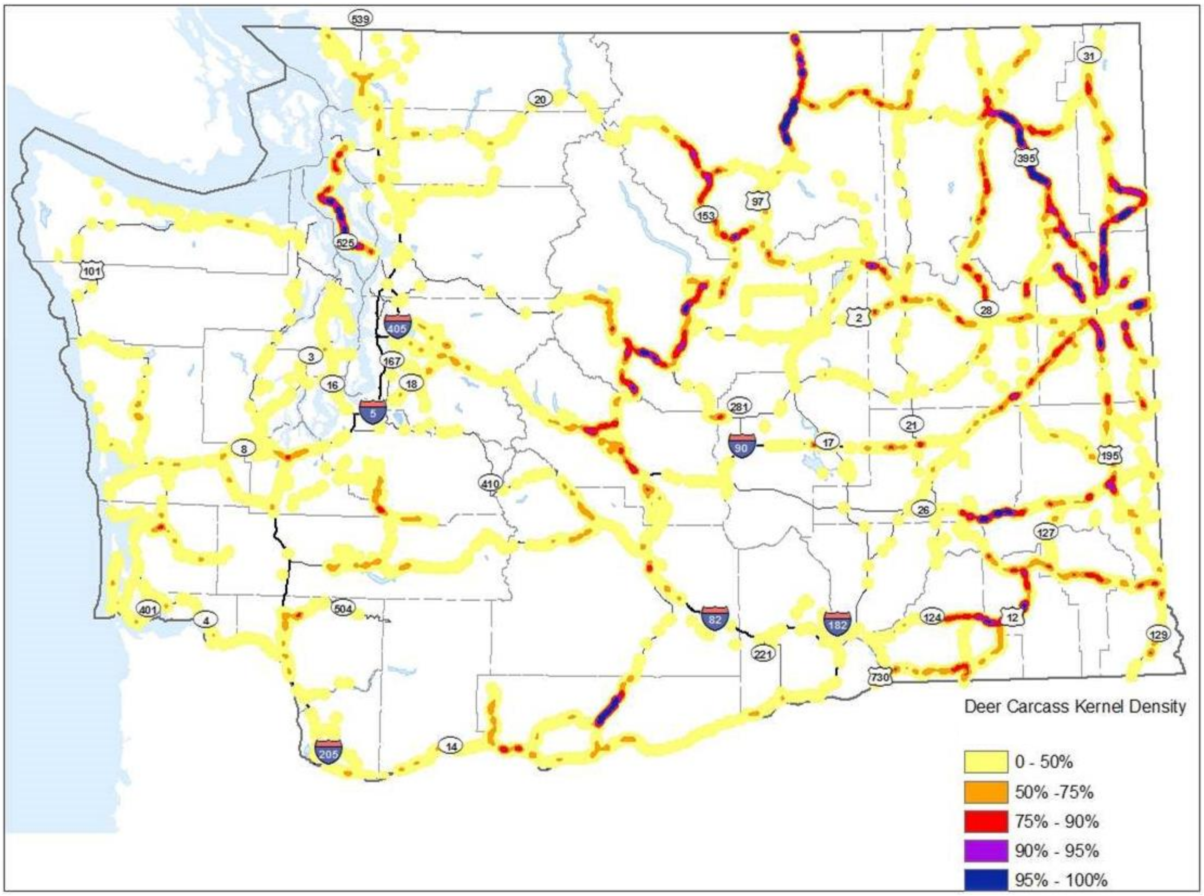
Hundreds of birds were observed by cameras placed on bridge underpasses and culverts, representing a relatively large use population that was discounted at the start of this study as likely to be minimal in size. Because of the technological limitations of the cameras currently in place, it was nearly impossible to say for certain where most of these individuals moved once they took flight: through the passage or away from it. The only confirmed crossings happened beneath bridge underpasses and were almost entirely Wild Turkeys. It would be interesting to see whether the smaller sparrows, thrushes, woodpeckers, and grouses that commonly searched for food on the ground in the mouths of culverts eventually passed through or whether these structures play a role in seasonal migrations as could be intuited from the movement of birds going predominantly north to south in the fall and south to north in the spring. The best method for achieving this in future research would be the use of motion video recording from deployed cameras, though this does increase the data size requirements and greatly extends the time required to process collected data. This idea of trying to record bird movement by video is, in fact, something that WSDOT biologists have agreed to explore with one of the cameras at the Cascades Dry Culvert East site soon to be changed out for one capable of recording video. Ideally, this will answer some of the lingering questions as to whether small birds will actually make use of these long, narrow culverts for flight. This could potentially add another population of interest in the ever-growing use community for Washington's wildlife passage structures.

Figure 1: I-90 Price/Noble Wildlife Overcrossing

Note: Final design intends to include foliage screening along edges of overpass.

Image courtesy of WSDOT

Figure 2: Deer Carcass Kernel Density Analysis

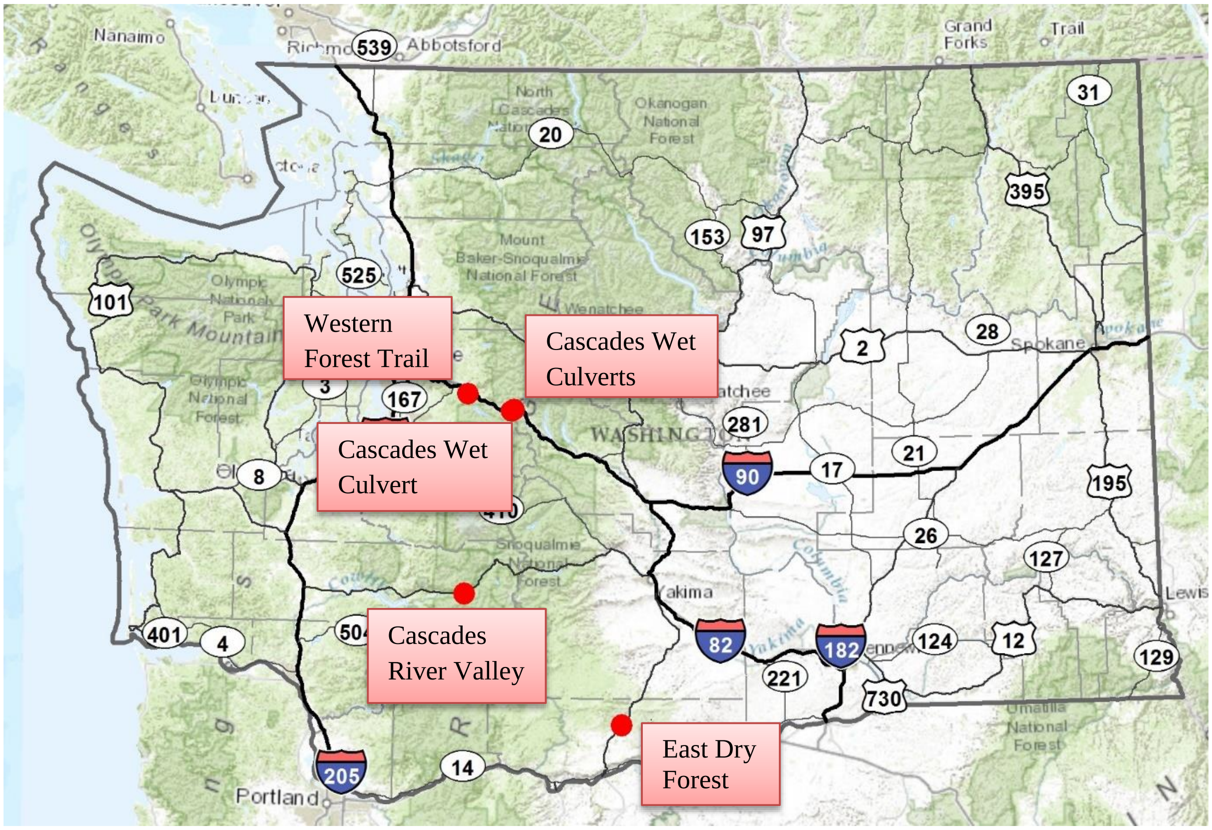


Note: 2009-2013 deer carcass kernel density analysis for Washington State. This map approximates those areas of Washington state roadways with the highest rate of collisions between deer and vehicles (McAllister & Plumley, 2015).

Figure 3: Camera Installation

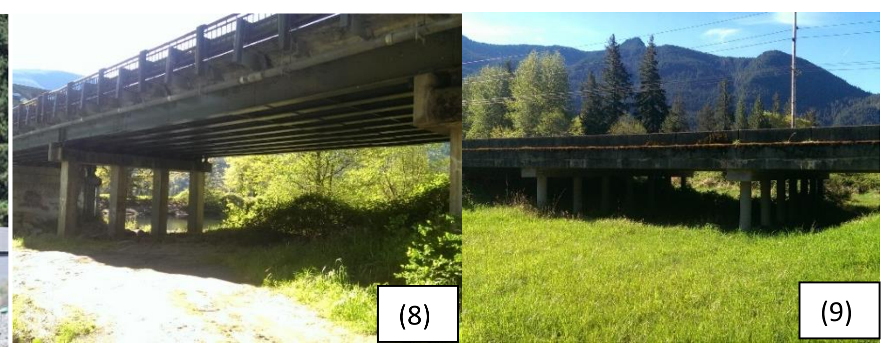
Note: Forms of camera installation: (1) Telespar; (2) Tree Mount; (3) Utility Box (Exterior); (4) Utility Box (Interior) Image 2 courtesy of Kelly McAllister

Figure 4: Study Areas



Note: Specific sites were selected from larger study for environmental and spatial variation, habitat connectivity and wildlife vehicle collision concerns, and because each site contained paired passage structures.

Figure 5: Study Structures



Note: (1) Western Forest Trail 1; (2) Western Forest Trail 2; (3) Cascades Wet Culvert; (4) Cascades Dry Culvert West; (5) Cascades Dry Culvert East; (6) East Dry Forest Culvert; (7) East Dry Forest Bridge; (8) Cascades River Valley Main Bridge; (9) Cascades River Valley Overflow Bridge.

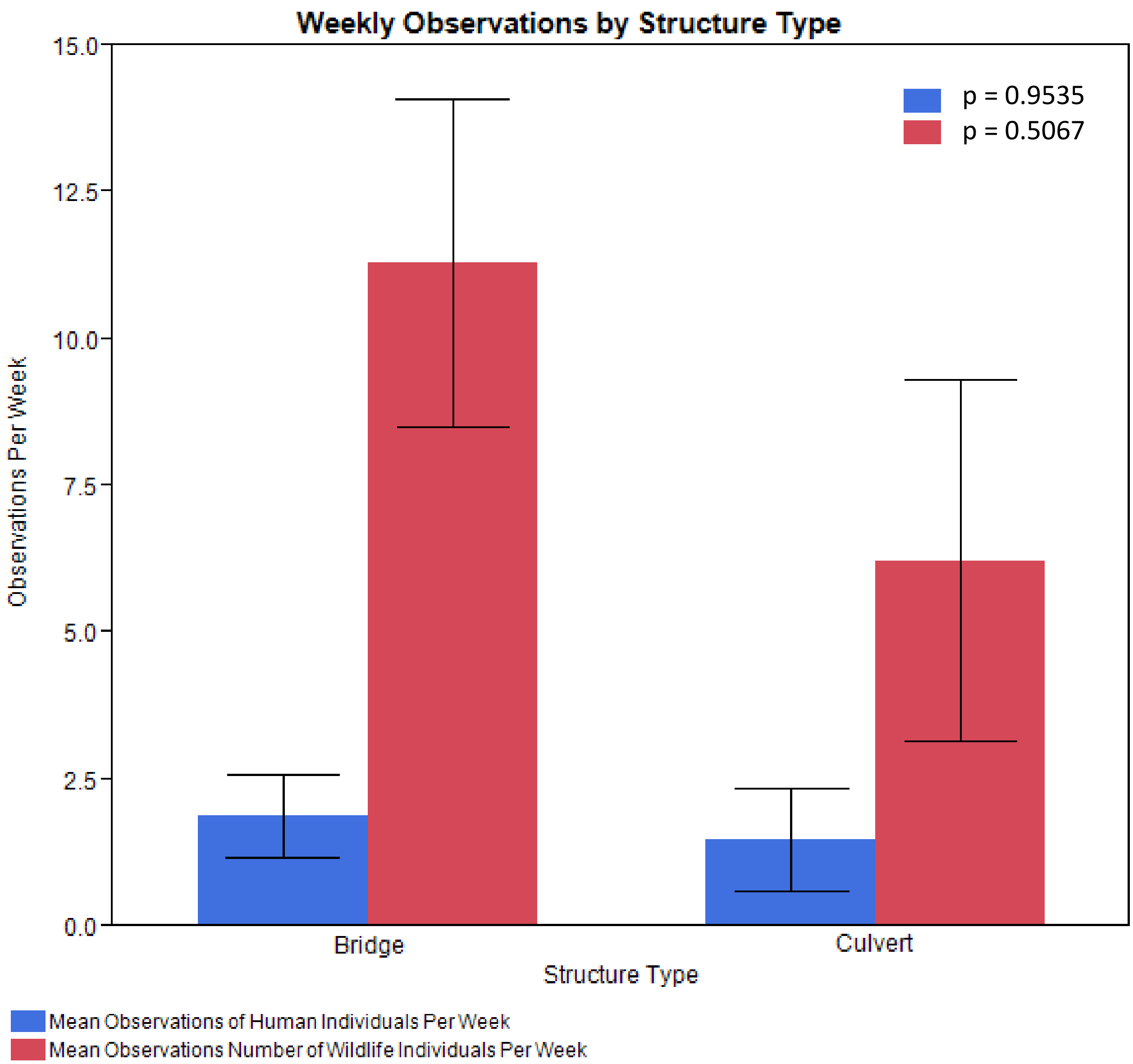
Images 1-7 courtesy of Kelly McAllister

Table 1: Usage of Study Structures and Confirmed Crossing Rates

Attributes	*Tunnels, Culverts, and Bridge Underpasses*								
	1	2	3	4	5	6	7	8	9
Crossing type	∩	∩	◻	○	○	○	∩	∩	∩
Dimensions									
Length (m)	12.2	12.2	18.3	62	62	12.2	12.2	12.2	12.2
Width (m)	4.6	12.2	1.8	1.8	1.2	1.5	43.9	91.4	67.1
Height (m)	3.0	3.0	1.2	2.5	1.2	1.5	6.1	4.6	2.5
Cross-sect. area (m^2)	13.8	36.6	2.16	3.53	1.13	1.77	268	420	168
Openness Ratio	1.13	3.0	0.12	0.06	0.02	0.15	22.0	34.4	13.8
Observations									
*Human & Related**	14383	39	27	174	23	42	96	202	55
Ungulate	44	377	0	0	0	131	628	324	1015
Large Carnivore Mam.	0	0	0	0	0	0	5	0	0
Small Carnivore Mam.	0	3	1	26	35	32	9	10	14
Small Prey Mam.	0	0	13	117	503	84	5	0	0
Bird	2	2	3	59	98	12	14	12	0
Total	14429	421	44	376	659	301	757	548	1084
Confirmed crossing %									
All Observations	100	99.5	27.3	57.4	35.2	22.9	81.4	74.5	23.6
Wildlife Only	100	99.5	11.8	28.2	33.6	18.9	83.2	65.3	20.8

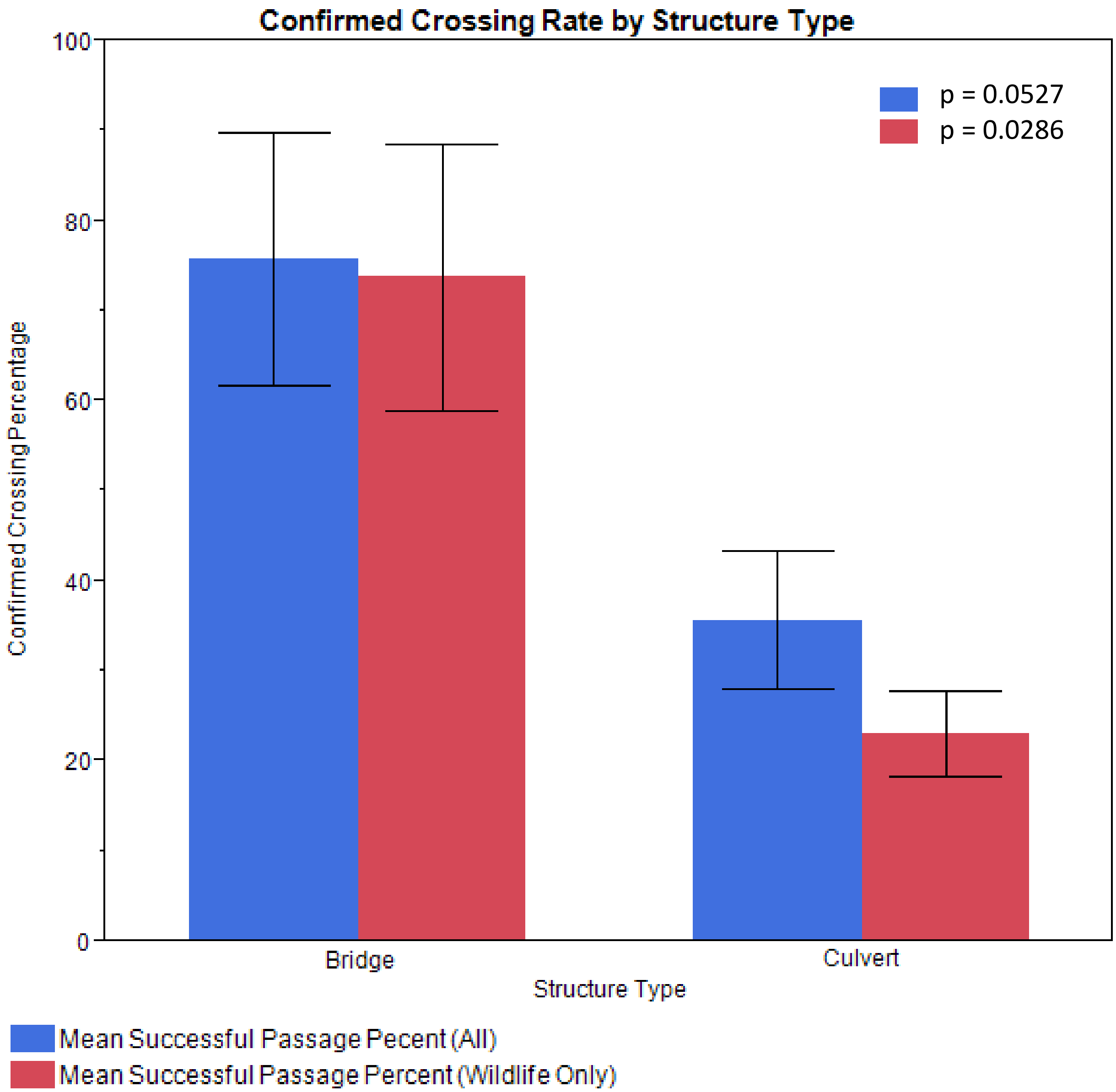
Note: * = This category includes humans and related domesticated species, specifically horses and canines. Domestic felines have been categorized as small carnivore mammals. ∩ = bridge underpass; ◻ = drainage box culvert; ○ = dry cylindrical metal culvert. Bridge widths exclude portion of underpass occupied by rivers.

Figure 6: Human and Wildlife Weekly Average Observations by Structure Type



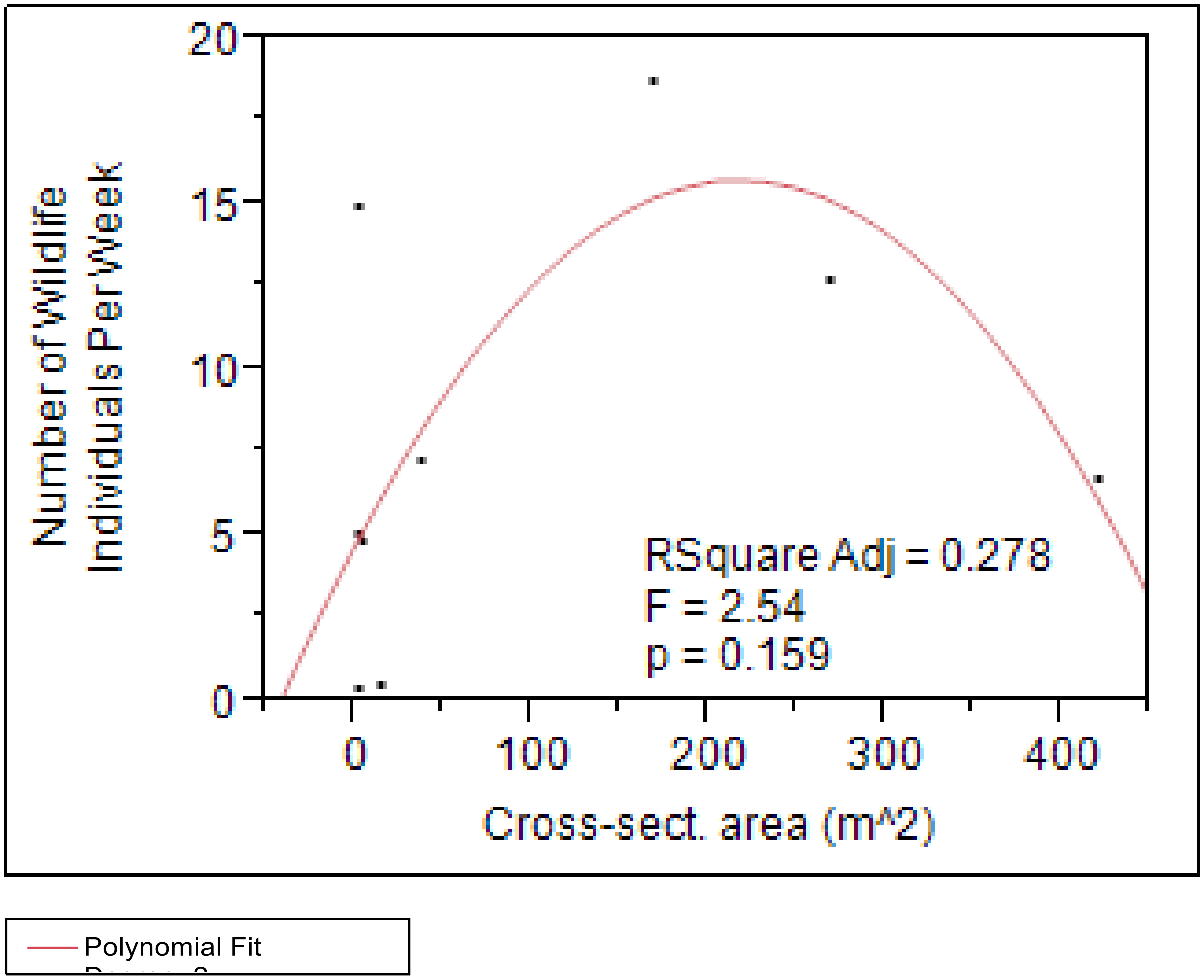
Note: Brackets constructed using 1 standard error from the mean. Seven sites included. Cascades Wet Culvert site excluded as irrelevant for this analysis due to environmental confounding variables. East Forest Trail 1 excluded as a major outlier in the dataset in that the value for human individuals per week at that site was approximately 33.5 times greater than the next highest value.

Figure 7: Confirmed Crossing Rates by Structure Type



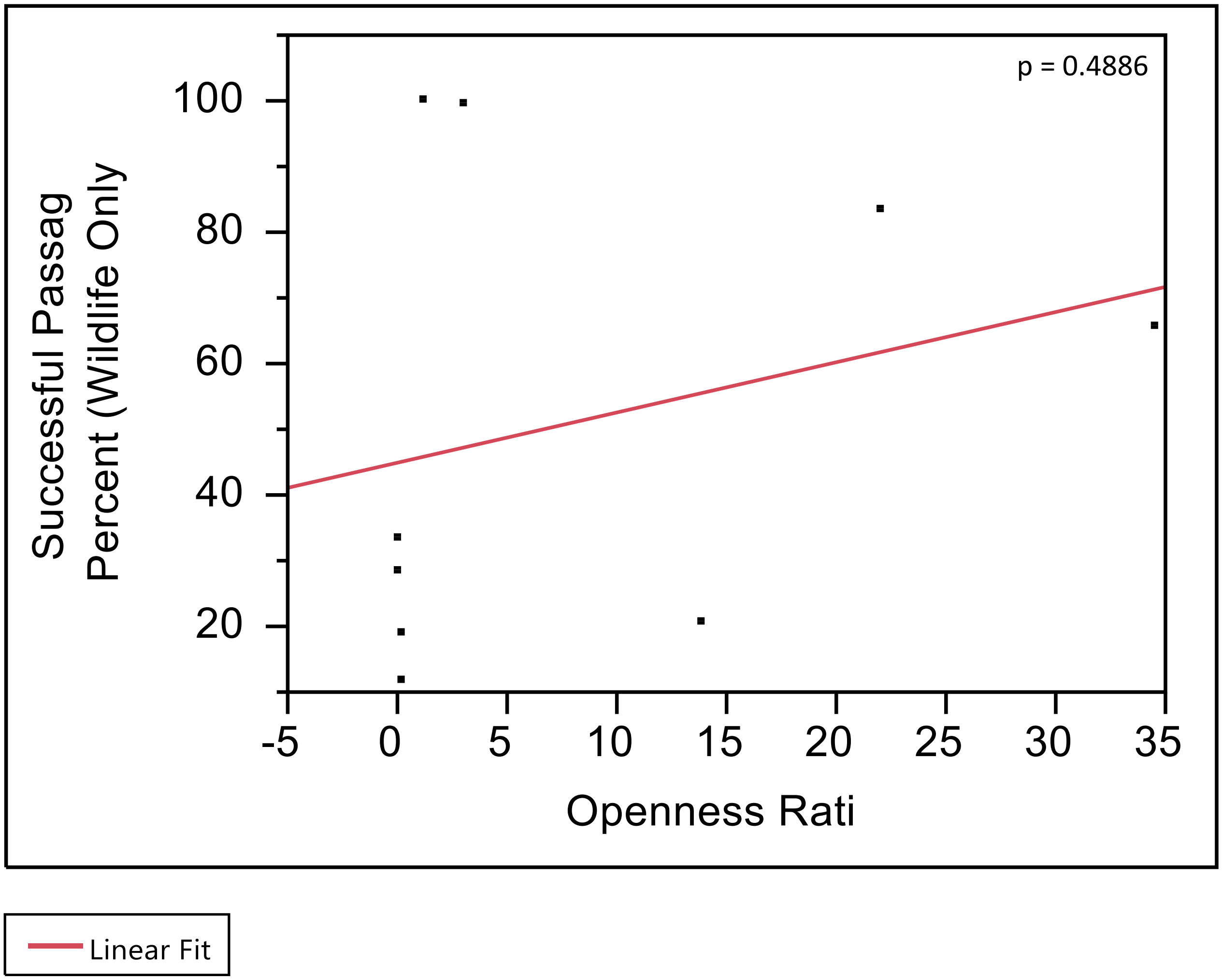
Note: As cameras were not set up to accurately assess bird passage rates, birds have been excluded from this analysis. Brackets constructed using 1 standard error from the mean.

Figure 8: Polynomial Fit Analysis of Wildlife Observations by Cross-sectional Area of Structure



Note: Number of Wildlife Individuals per Week = 7.1458654 + 0.0539685*Cross-sect. area - 0.0002336*(Cross-sect. area - 101.666) ^{2}. This analysis is not significant at the $p < 0.05$ level, but seems to indicate a pattern of increasing observations as cross-section increases before reaching a point of diminishing returns. It is probable that the limited camera coverage of larger structures played a major role in the leveling-off of wildlife observations and likely explains the eventual decrease as well.

Figure 9: Bivariate Fit Analysis of Wildlife Observations by Openness Ratio of Structure

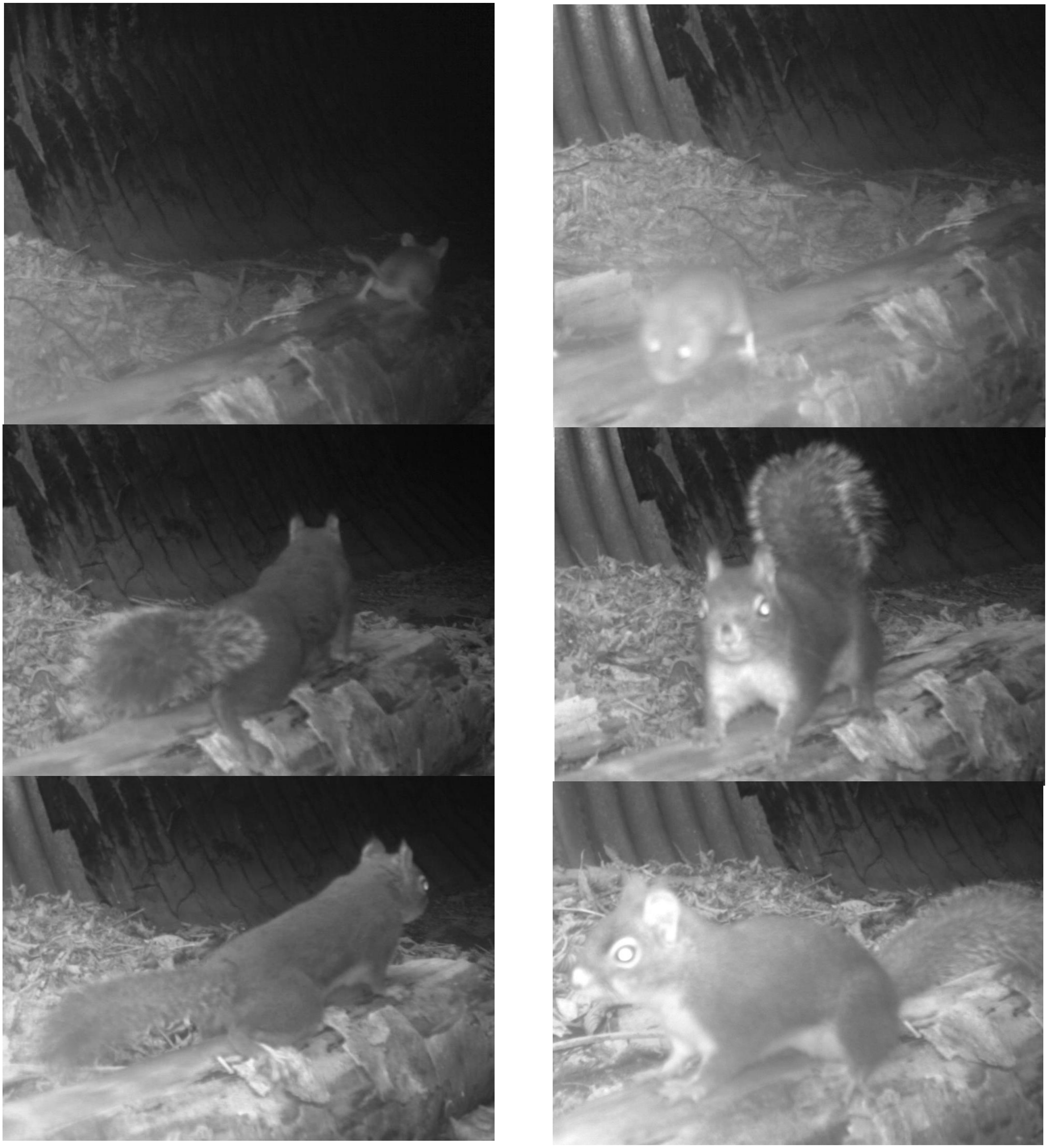


Note: Successful Wildlife Passage Rate = 44.915572 + 0.7645356*Openness Ratio. This analysis is not significant at the $p < 0.05$ level, but seems to indicate a pattern of increasingly successful crossings as openness ratio (height*width/length) increases.

Figure 10: Wildlife Use of Tree Branches to Enter Culverts

Note: Bushy-tailed woodrat use of placed woody debris at Cascades Dry Culvert East. Bottom two rows show assumed use for exit as the camera was not triggered until the animal was past the branch, but the animal being positioned on far side of camera (in contrast to row 1) is suggestive. Image dates by row from top: 11/11/2015, 11/13/2015, 11/18/2015.

Figure 11: Wildlife Use of Branches That Do Not Enter Culvert



Note: Deer mouse and Douglas squirrel hesitation at end of placed woody debris that does not enter structure mouth at Cascades Dry Culvert East. Image dates by row from top: 3/12/2015, 3/17/2015, 4/9/2015. All animals eventually crossed without using the available branch.

Table 2 Part 1/2: Crossings by Species

Species	*Crossings*				*Confirmed crossings as a % of total observations*
	Yes	Unk.	No	Total	
Human *(Homo sapiens)*	3255	4	109	3368	96.64
Human & Canine	11356	0	2	11358	99.98
Canine *(Canis familiaris)*	4	3	0	7	57.14
Human & Horse *(Equus ferus caballus)*	83	0	0	83	100
Human, Horse, & Canine	222	0	0	222	100
All Humans & Related	14920	7	111	15038	99.22
Elk *(Cervus canadensis)*	705	26	752	1483	47.54
Black-Tailed Deer *(Odocoileus hemionus)*	674	36	211	921	73.18
Cattle *(Bos taurus)*	0	0	42	42	0
All Ungulates	1379	62	1005	2446	56.38
Cougar *(Puma concolor)*	5	0	0	5	100
All Large Carnivore Mammals	5	0	0	5	100
Bobcat *(Lynx rufus)*	45	3	0	48	93.75
Raccoon *(Procyon lotor)*	7	3	0	10	70
Coyote *(Canis latrans)*	3	5	14	22	13.64
Domestic Cat *(Felis catus)*	6	2	2	10	60
Long-Tailed Weasel *(Mustela frenata)*	13	4	7	24	54.17
Short-Tailed Weasel *(Mustela erminea)*	1	0	0	1	100
Common Opossum *(Didelphimorphia)*	2	0	0	2	100
Striped Skunk *(Mephitis mephitis)*	11	0	0	11	100
All Small Carnivore Mammals	88	17	23	128	68.75

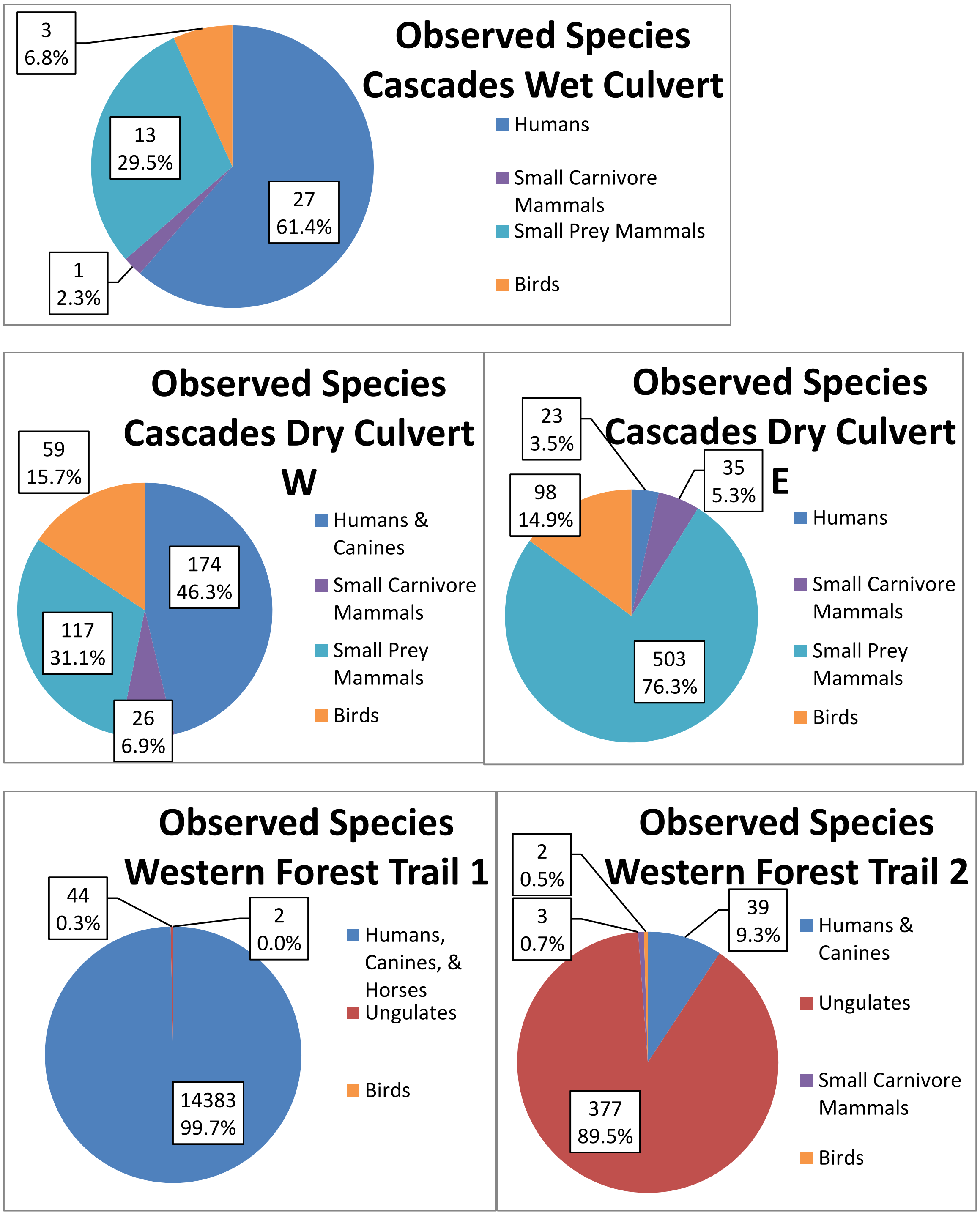
Note: Use of culverts and bridge underpasses differentiated by species, including calculation of confirmed successful passages as a percentage of total observations.

Table 2 Part 2/2: Crossings by Species

Species	*Crossings*				*Confirmed crossings as a % of total observations*
	Yes	Unk.	No	Total	
Mountain Beaver *(Aplodontia rufa)*	3	1	0	4	75
Townsend's Chipmunk *(Neotamias townsendii)*	4	6	12	22	18.18
Douglas Squirrel *(Tamiasciurus douglasii)*	93	11	40	144	64.58
Bushy-Tailed Woodrat *(Neotoma cinerea)*	58	33	45	136	42.65
Deer Mouse *(Peromyscus maniculatus)*	39	6	168	213	18.31
Pika *(Ochotona princeps)*	0	1	3	4	0
Snowshoe Hare *(Lepus americanus)*	13	6	0	19	68.42
Long-Tailed Vole *(Microtus longicaudus)*	1	5	1	7	14.29
California Ground Squirrel *(Otospermophilus beecheyi)*	3	4	8	15	20
Northern Flying Squirrel *(Glaucomys sabrinus)*	0	0	1	1	0
Unknown Species	40	67	127	234	17.09
All Small Prey Mammals	254	140	405	799	31.79
Varied Thrush *(Ixoreus naevius)*	0	1	36	37	0
American Robin *(Turdus migratorius)*	2	4	89	95	2.11
Dark-Eyed Junco *(Junco hyemalis)*	1	0	6	7	14.29
Wild Turkey *(Meleagris gallopavo)*	6	2	6	14	42.86
Steller's Jay *(Cyanocitta stelleri)*	0	0	20	20	0
Northern Flicker *(Colaptes auratus)*	0	0	1	1	0
Ruffed Grouse *(Bonasa umbellus)*	0	0	1	1	0
Unknown Species	6	2	20	28	21.43
All Birds	15	9	179	203	7.39
All Records	16744	235	1723	18702	89.53

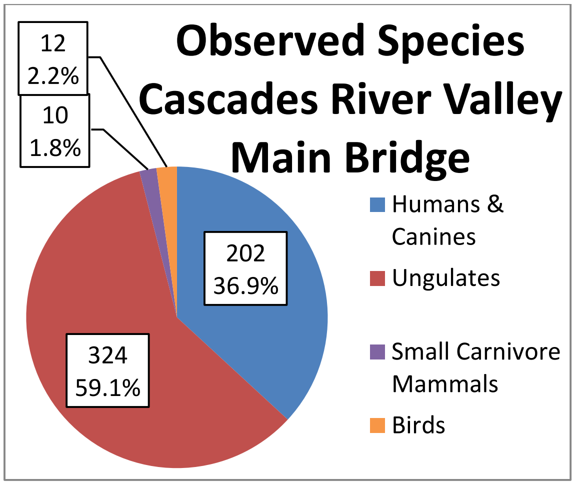
Note: Use of culverts and bridge underpasses differentiated by species, including calculation of confirmed successful passages as a percentage of total observations.

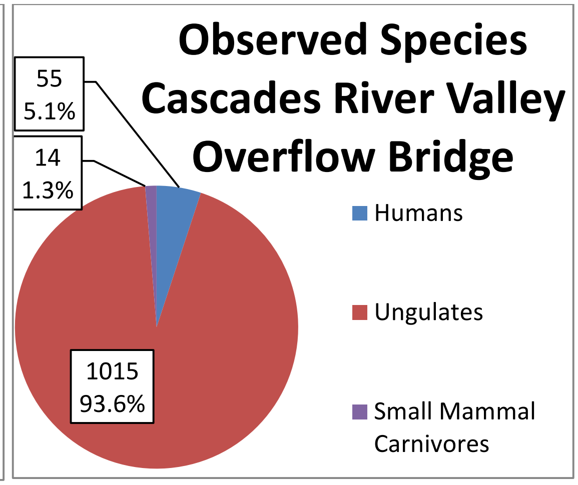
Figure 12 Part 1/2: Observed Species by Structure

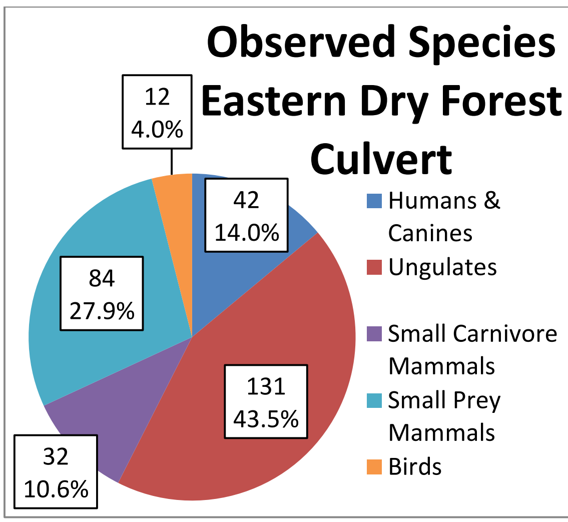


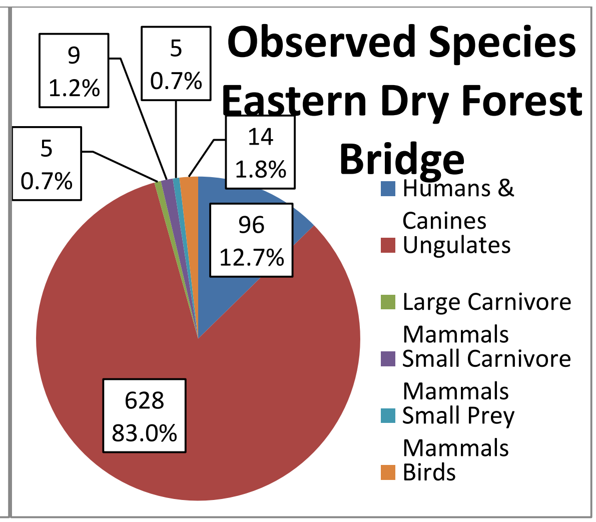
Note: Numbers indicate total observed individuals over a one-year period. Percentages indicate percentage of total observations over a one-year period.

Figure 12 Part 2/2: Observed Species by Structure



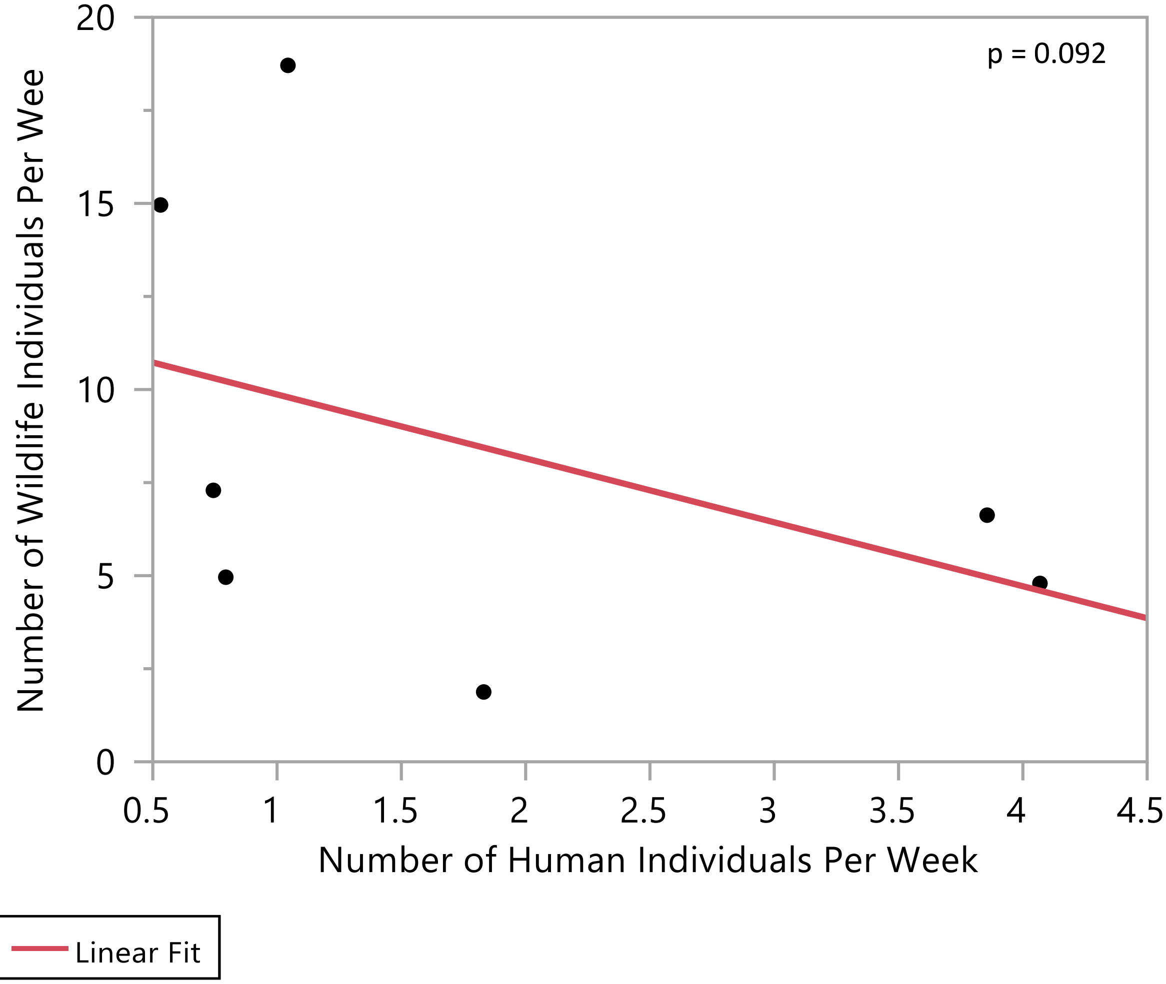






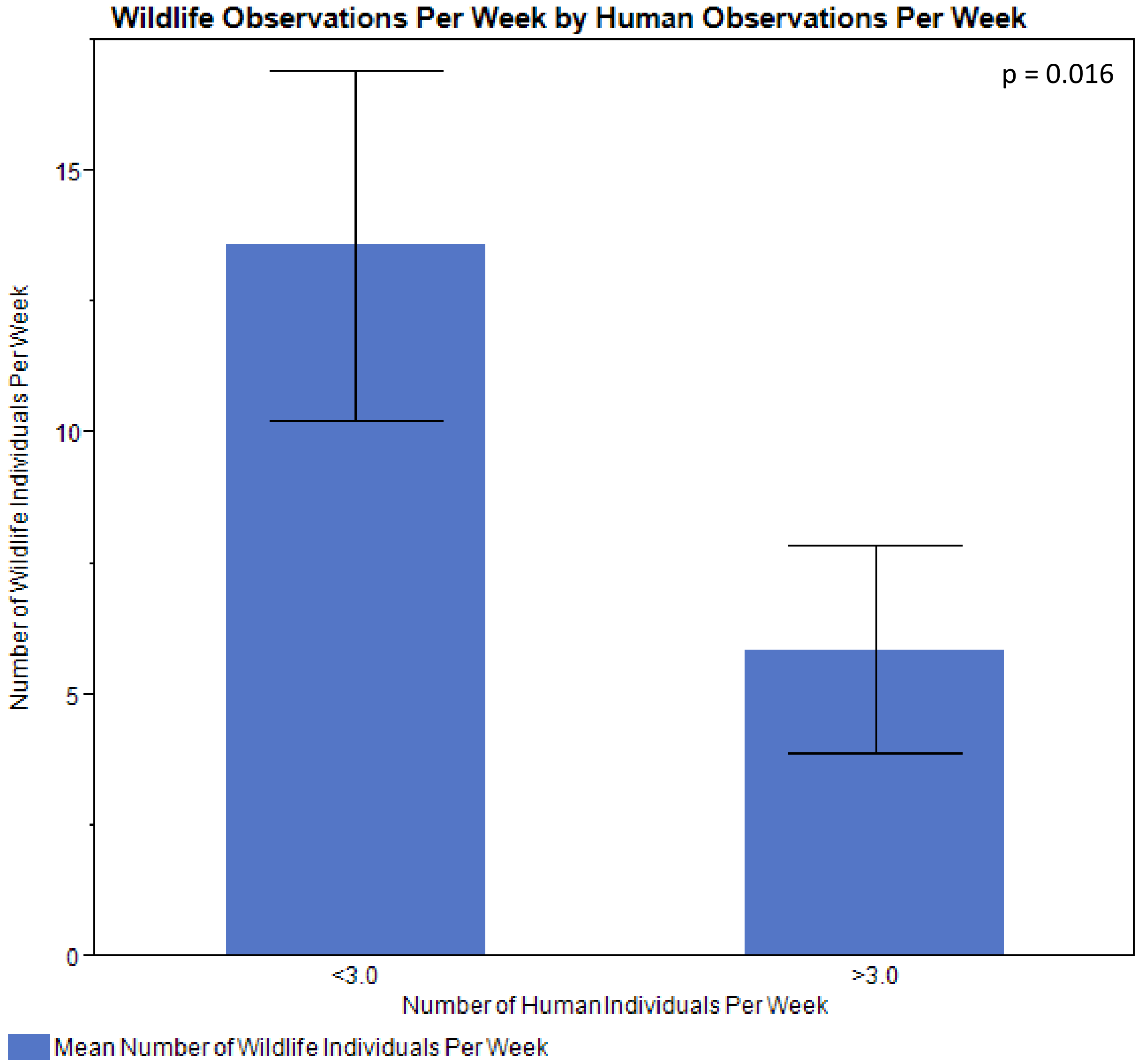
Note: Numbers indicate total observed individuals over a one-year period. Percentages indicate percentage of total observations over a one-year period.

Figure 13: Bivariate Fit of Number of Wildlife Individuals per Week by Number of Human Individuals per Week



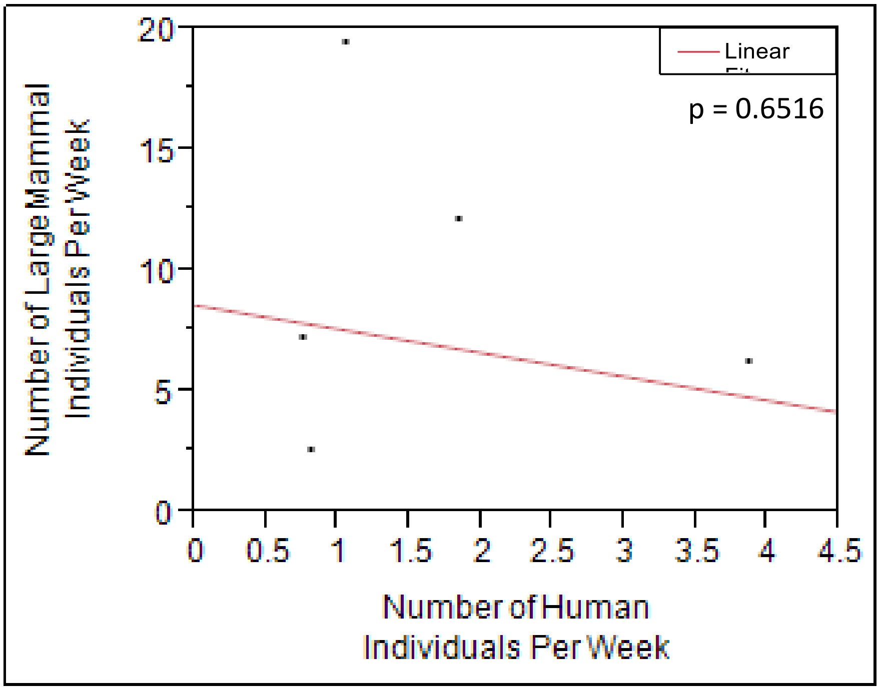
Note: Number of Wildlife Individuals per Week = 11.585422 - 1.7173899*Number of Human Individuals per Week. Western Forest Trail 1 and Cascades Wet Culvert are excluded as major outliers in the dataset.

Figure 14: **One-way Analysis of Number of Wildlife Individuals per Week by Number of Human Individuals per Week Categorical**

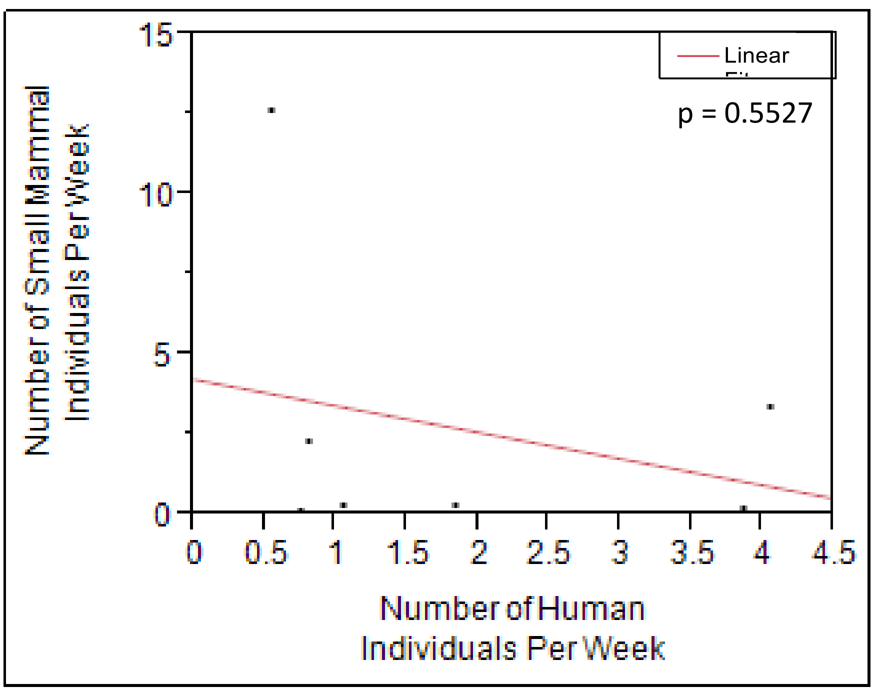


Note: One-way ANOVA showing a significant divergence in wildlife individual weekly use rates for passage structures when compared to whether the human individual weekly use rate for the same structures was above or below 3 individuals per week.

Figure 15: Bivariate Fit of Number of Large & Small Mammal Individuals Per Week By Number of Human Individuals Per Week

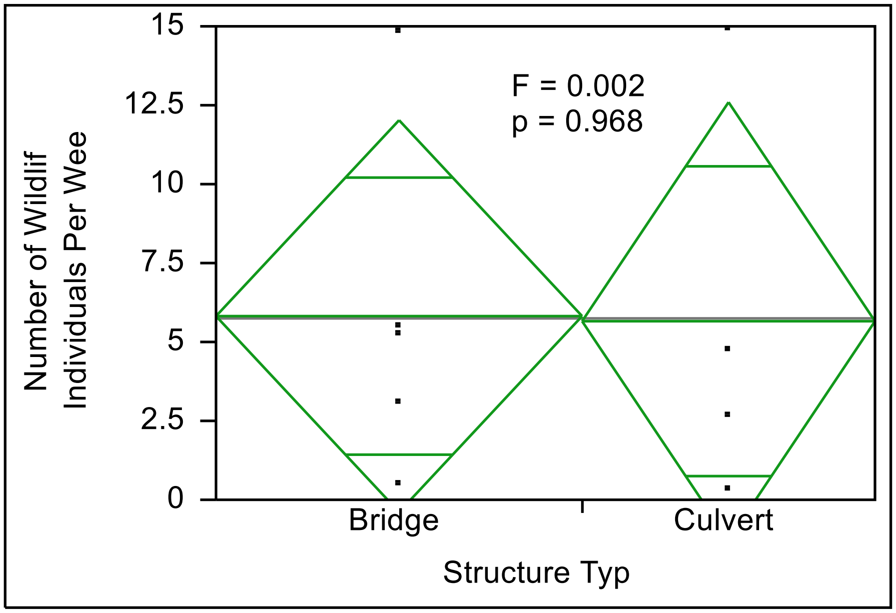


Note: Number of Large Mammal Individuals Per Week = 8.5888586 - 0.9845716*Number of Human Individuals Per Week. Western Forest Trail 1 and Cascades Wet Culvert are excluded as major outliers in the dataset.

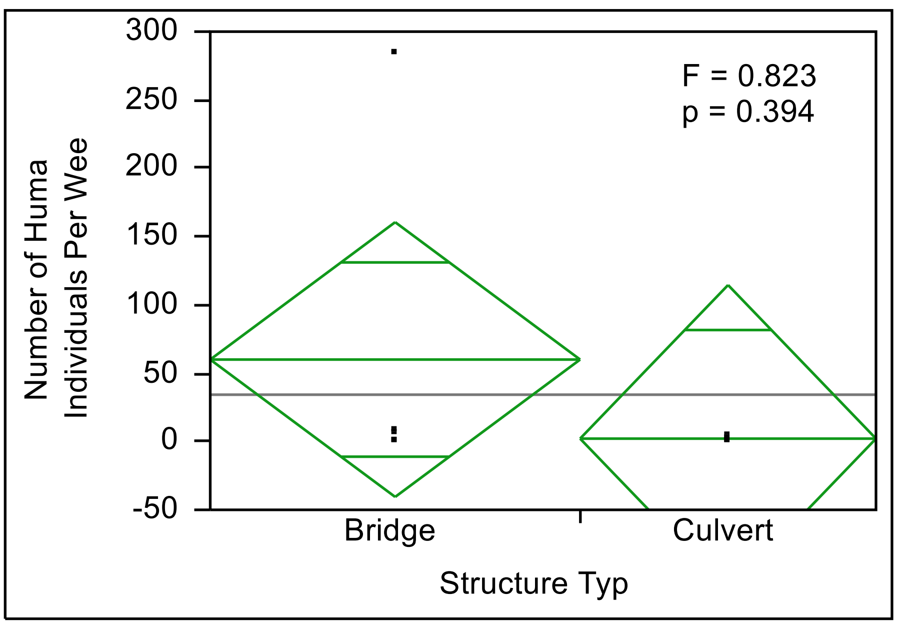


Note: Number of Small Mammal Individuals Per Week = 4.2276624 - 0.826101*Number of Human Individuals Per Week. Western Forest Trail 1 and Cascades Wet Culvert are excluded as major outliers in the dataset.

Figure 16: One-way Analysis of Number of Wildlife Individuals per Week by Structure Type



One-way Analysis of Number of Human Individuals per Week by Structure Type



Note: One-way ANOVA of wildlife and human weekly passage rates contrasted by the type of structure being observed. The first graph shows that across the 5 bridges and 4 culverts observed, wildlife showed no preference for either structure with the current human use patterns in place. The second graph that there may be a preference for humans to use bridge underpasses rather than culverts, but the analysis is statistically insignificant.

References

Ager, A. A., Johnson, B. K., Kern, J. W., & Kie, J. G. (2003). Daily and seasonal movements and habitat use by female rocky mountain elk and mule deer. *Journal of Mammalogy, 84(3)*, 1076-1088.

Anderson, G., Freeman, M., Freeman, B., Straight, C., Hagler, M., & Peterson, J. (2012). Dealing With Uncertainty When Assessing Fish Passage Through Culvert Road Crossings. *Environmental Management*, *50*(3), 462–477.

Aresco, M. (2005). The effect of sex-specific terrestrial movements and roads on the sex ratio of freshwater turtles. *Biological Conservation*,*123*, 37–44. Retrieved from http://www.sciencedirect.com.bay.evergreen.edu/science/article/pii/S0006320704004264

Baxter-Gilbert, J., Lesbarrères, D., & Litzgus, J. (2013). On the Road Again: Measuring the Effectiveness of Mitigation Structures for Reducing Reptile Road Mortality and Maintaining Population Connectivity (p. 16). Presented at the 2013 International Conference on Ecology and Transportation, Scottsdale, Arizona, USA. Retrieved from http://www.icoet.net/ICOET_2013/documents/papers/ICOET2013_Paper104D_BaxterGilbert%20_et_al.pdf

Cain, A. T., Tuovila, V. R., Hewitt, D. G., & Tewes, M. E. (2003). Effects of a highway and mitigation projects on bobcats in Southern Texas. *Biological Conservation, 114*, 189-197.

Clevenger, A. P., Chruszcz, B., Gunson, K., Wierzchowski, J. (2002). Roads and wildlife in the Canadian Rocky Mountain Parks – movements, mortality and mitigation. Final report. Prepared for Parks Canada, Banff, Alberta, Canada.

Clevenger, A. P., & Waltho, N. (2000). Factors Influencing the Effectiveness of Wildlife Underpasses in Banff National Park, Alberta, Canada. *Conservation Biology*, *14*(1), 47–56.

Clevenger, A. P., & Waltho, N. (2005). Performance indices to identify attributes of highway crossing structures facilitating movement of large mammals. *Biological Conservation, 121*(3), 453-464.

Connolly-Newman, H., Huijser, M., Broberg, L., Nelson, C., & Camel-Means, W. (2013). Effect of Cover on Small Mammal Movements Through Wildlife Underpasses Along US Highway 93 North, Montana, USA. (p. 12). Presented at the 2013 International Conference on Ecology and Transportation, Scottsdale, Arizona, USA. Retrieved from http://www.icoet.net/icoet_2013/documents/papers/ICOET2013_Paper401C_ConnollyNewman_et_al.pdf

Craighead Institute. (2010, June 24). *black bear using culvert* [Video file]. Retrieved from https://www.youtube.com/watch?v=l95GmKHAOg0.

Dellinger, J. A., Proctor, C., Steury, T. D., Kelly, M. J., & Vaughan, M. R. (2013). Habitat selection of a large carnivore, the red wolf, in a human-altered landscape. *Biological Conservation*, *157*, 324-330.

Dodd, C. K., Jr., Barichivich, W. J., & 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), 619-631.

Ensing, E. P., Ciuti, S., de Wijs, F. A. L. M., Lentferink, D. H., ten Hoedt, A., Boyce, M. S., & Hut, R. A. (2014). GPS Based Daily Activity Patterns in European Red Deer and North American Elk (Cervus elaphus): Indication for a Weak Circadian Clock in Ungulates. *PLoS ONE, 9(9)*, 1-11.

Erickson, W. P., Johnson, G. D., & Young Jr., D. P. (2005). *A Summary and Comparison of Bird Mortality from Anthropogenic Causes with an Emphasis on Collisions* (General Technical Report No. PSW-GTR-191) (pp. 1029–1042). USDA Forest Service. Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr191/Asilomar/pdfs/1029-1042.pdf

Fahrig, L., & Rytwinski, T. (2009). Effects Of Roads On Animal Abundance: An Empirical Review And Synthesis. *Ecology and Society*, *14*(1), 21.

Foresman, K. R. (2004). *The effects of highways on fragmentation of small mammal populations and modifications of crossing structures to mitigate such impacts*. Helena, MT: Montana Dept. of Transportation, Research Program ; Springfield, Va.

Forman, R. T. T., Sperling, D., Bissonette, J. A., Clevenger, A. P., Cutshall, C. D., Dale, V. H., … Winter, T. C. (2003). *Road Ecology: Science and Solutions*. Washington D.C.: Island Press.

Foster, M. L., & Humphrey, S. R. (1995). Use of Highway Underpasses by Florida Panthers and Other Wildlife. *Wildlife Society Bulletin, 23(1*), 95-100.

Gagnon, J. W., Dodd, N. L., Ogren, K. S., & Schweinsburg, R. E. (2011). Factors Associated With Use of Wildlife Underpasses and Importance of Long- Term Monitoring. *The Journal of Wildlife Management, 75*(6), 1477-1487.

Gibbons, J. W., & Andrews, K. M. (2004). PIT tagging: Simple technology at its best. *BioScience 54*, 447-454.

Gunson, K. E., Mountrakis, G., & 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),* 1074-1085.

Hartmann, M. (2003). Evaluation of Wildlife Crossing Structures: Their Use and Effectiveness. Wildlands CPR website.

Hemson, G., Maclennan, S., Mills, G., Johnson, P., & Macdonald, D. (2009). Community, lions, livestock and money: A spatial and social analysis of attitudes to wildlife and the conservation value of tourism in a human-carnivore conflict in Botswana. *Biological Conservation, 142(11),* 2718-2725.

Huijser, M., Fairbank, E., Camel-Means, W., & Purdum, J. (2013). *US 93 North Post-Construction Wildlife-Vehicle Collision and Wildlife Crossing Monitoring and Research on the Flathead Indian Reservation between Evaro and Polson, Montana Annual Report 2013* (p. 23). Helena, Montana: Western Transportation Institute, Montana State University. Retrieved from http://www.mdt.mt.gov/other/research/external/docs/research_proj/wildlife_crossing/phaseii/annual_2013.pdf

Huijser, M. P., & Bergers, P. J. M. (2000). The effect of roads and traffic on hedgehog (Erinaceus europaeus) populations. *Biological Conservation*, *95*(1), 111–116. doi:10.1016/S0006-3207(00)00006-9

Huijser, M. P., McGowen, P., Fuller, J., Hardy, A., Kociolek, A., Clevenger, A. P., … Ament, R. (08-07). *Wildlife-vehicle collision reduction study. Report to congress.* (p. 260). U.S. Department of Transportation, Federal Highway Administration.

Jackson, S., & Tyning, T. (n.d.). Salamander Tunnels [Government Website]. Retrieved from http://www.fhwa.dot.gov/environment/critter_crossings/salamand.cfm

Jacobson, S. (2002) Using Wildlife Behavioral Traits to Design Effective Crossing Structures. Wildlife Crossings Toolkit, U.S. Department of Agriculture's Forest Service.

Kertson, B. N., Spencer, R. D., Marzluff, J. M., Hepinstall-Cymerman, J., & Grue, C. E. (2011). Cougar space use and movements in the wildland-urban landscape of western Washington. *Ecological Applications, 21(8)*, 2866-2881.

Kintsch, J., & Cramer, P. (2011). *Permeability of Existing Structures for Wildlife: Developing a Passage Assessment System* (No. WA-RD 777.1) (p. 188). Olympia, WA: Washington State Department of Transportation.

Leedy, D. L., Franklin, T. M., & Hekimian, E. G. (1975). Highway-wildlife relationships: Vol. 2. (Report No. FHWA RD 76 5). Final report. Prepared for Federal Highway Administration, Washington, D.C., USA.

Little, S. J., Harcourt, R. G., & Clevenger, A. P. (2005). Do wildlife passages act as prey-traps? *Biological Conservation, 107*(2), 135-145.

Litvaitis, J., & Tash, J. (2008). An Approach Toward Understanding Wildlife-Vehicle Collisions. *Environmental Management, 42*(4), 688–697.

Loss, S. R., Will, T., & Marra, P. P. (2014). Estimation of bird-vehicle collision mortality on U.S. roads. *The Journal of Wildlife Management,78*(5), 763–771.

Mata, C., Hervás, I., Herranz, J., Suárez, F., & Malo, J. E. (2008). Are motorway wildlife passages worth building? Vertebrate use of road- crossing structures on a Spanish motorway. *Journal of Environmental Management 88*. 407-415.

Macdonald, S. (1998). *Planning Trails with Wildlife in Mind: A Handbook for Trail Planners* (Handbook) (p. 56). Denver, Colorado, USA: Colorado State Parks. Retrieved from http://atfiles.org/files/pdf/Trails-for-Wildlife-Handbk.pdf

McAllister, K., & Plumley, S. (2015). Deer Collision Hotspot and Kernel Density Analysis for Washington State Highways. Final report. Prepared for Washington State Department of Transportation, Olympia, Washington, USA.

McAllister, K., Reister, M., Bruno, R., Dillin, L., Volsen, D., & Wisen, M. (2014). A Wildlife Barrier Fence North of Wenatchee, WA – Learning Experiences Involving

Rugged Country and Custom Designed Wildlife Guards and Jumpouts. Final report. Prepared for Washington State Department of Transportation, Olympia, Washington, USA.

McCollister, M. F., & van Manen, F. T. (2010). Effectiveness of Wildlife Underpasses and Fencing to Reduce Wildlife–Vehicle Collisions. *Journal of Wildlife Management*, *74*(8), 1722–1731. Retrieved from http://www.bioone.org.bay.evergreen.edu/doi/abs/10.2193/2009-535

National Public Radio Staff. (2014). Why Did The Mountain Lion Cross The Freeway? To Breed. Retrieved from http://www.npr.org/2014/10/19/357404731/why-did-the-mountain-lion-cross-the-freeway-to-breed

Niemi, M., Jääskeläinen, N. C., Nummi, P., Mäkelä, T., & Norrdahl, K. (2014). Dry paths effectively reduce road mortality of small and medium-sized terrestrial vertibrates. *Journal of Environmental Management, 144*, 51-57.

Olsson, M. P. O., Widén P., & Larkin, J. L. (2008). Effectiveness of a highway overpass to promote landscape connectivity and movement of moose and roe deer in Sweden. *Landscape and Urban Planning, 85*(2), 133-139.

O'Malley, P. G. (2004). The Leading Edge: Managers discover there's more to a right of way than vegetation. *Erosion Control*. Retrieved from http://www.erosioncontrol.com/EC/Articles/The_Leading_Edge_4301.aspx

Owens, A. K., Moselely, K. R., McCay, T. S., Castleberry, S. B., Kilgo, J. C., & Ford, W. M. (2008). Amphibian and reptile community response to coarse woody debris manipulations in upland loblolly pine (*Pinus taeda*) forests. *Forest Ecology and Management*, *256(12)*, 2078-2083.

Oxley, D. J., Fenton, M. B., & Carmody, G. R. (1974). The Effects of Roads on Population of Small Mammals. *Journal of Applied Ecology*, *11(1)*, 51-59.

Pedevillano, C., & Gerald Wright, R. (1987). The influence of visitors on mountain goat activities in Glacier National Park, Montana. *Biological Conservation*, *39*(1), 1–11. doi:10.1016/0006-3207(87)90002-4

Peterson, C. (2014, October 13). Sage Grouse Uprising? Rare pictuers catch Wyoming sage grouse using wildlife underpass. *Casper Star-Tribune Communications*. Retrieved from http://trib.com/lifestyles/recreation/rare-pictures-catch-wyoming-sage-grouse-using-wildlife-underpass/article_e7beecbb-f2c8-58a3-8156-31bd27b9b8d3.html

Phillips, G. E., Alldredge, W., & Andree, W. W. (2001). MITIGATING DISTURBANCE OF MIGRATING MULE DEER CAUSED BY CYCLISTS AND PEDESTRIANS AT A HIGHWAY UNDERPASS NEAR VAIL, COLORADO. In *2001 International Conference on Ecology and Transportation*. Keystone, Colorado. Retrieved from http://www.icoet.net/downloads/Posters.pdf#page=24

Puky, M., Mester, B., & Mechura, T. (2013). How Much Does Size Matter? Tunnel Size Significantly Influence Amphibian Crossings at Parassapuszta, Hungary According to Mid-Term Monitoring used to Delineate Mitigation Measure Improvement Plans. Presented at the 2013 International Conference on Ecology and Transportation, Scottsdale, Arizona, USA. Retrieved from http://www.icoet.net/icoet_2013/documents/posters/ICOET2013_PosterImageP29_Puky_et_al.pdf

Rodriguez, A., Crema, G., & Delibes, M. (1996). Use of Non-Wildlife Passages Across a High Speed Railway by Terrestrial Vertebrates. *Journal of Applied Ecology*, *33*(6), 1527–1540. Retrieved from http://www.jstor.org.bay.evergreen.edu/stable/pdfplus/2404791.pdf?acceptTC=true&jpdConfirm=true

Ruiz-Capillas, P., Mata, C., & Male, J. E. (2013). Road verges are refuges for small mammal populations in extensively managed Mediterranean landscapes. *Biological Conservation*, *158*, 223–229.

Rytwinski, T., van der Ree, R., Cunnington, G. M., Fahrig, L., Findlay, C. S., Houlahan, J., Jaeger, J. A. G., Soanes, K., & van der Grift, E. (2015). Experimental study designs to improve the evaluation of road mitigation measures for wildlife. *Journal of Environmental Management, 154 (1),* 48-64.

Serronha, A. M., Mateus, A. R., Eaton, F., Santos-Reis, M., & Grilo, C. (2013). Towards effective culvert design: monitoring seasonal use and behavior by Mediterranean mesocarnivores. *Envionmental Monitoring and Assessment, 185(8), 6235-6246*.

Shepherd, B., & Whittington, J. (2006). Response of Wolves to Corridor Restoration and Human Use Management. *Ecology and Society, 11(2),* 1. Retrieved from http://www.ecologyandsociety.org/vol11/iss2/art1/

Smith, D. (2003). Monitoring Wildlife Use and Determining Standards for Culvert Design. Final report presented to the Florida Department of Transportation for Contract BC354-34, Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, Florida.

Smith, J. (2011). *I-90: Integrating Stewardship into the Highway Design*. Yakima, WA: Washington State Department of Transportation. Retrieved from http://www.wsdot.wa.gov/NR/rdonlyres/EC7FEC4D-27BE-4601-B7AD-F8FC1BB063FE/0/I90ENVIROFolioweb.pdf

Soulé, M. E. (2000). Is connectivity necessary? Presented at the Missing Linkages: Restoring Connectivity to the California Landscape Conference, San Diego, California, USA.

Southall, P. (n.d.). Amphibian-Reptile Wall and Culverts [Government Website]. Retrieved from http://www.fhwa.dot.gov/environment/critter_crossings/amphibin.cfm

Sullivan, M. (2014). *A Temporal Analysis of Elk Movement in Relation to Washington's Transportation Infrastructure* (Master's Thesis). The Evergreen State College, Olympia, Washington, USA.

United States Bureau of the Census. (2000). The Census Bureau on Prospects for US Population Growth in the Twenty-First Century. *Population & Development Review, 26(1),* 197-200.

Washington State Department of Transportation. (2015). *Wildlife Carcass Removal Database* [Data file].

Washington State Patrol. (2015). *Vehicle Collision Database* [Data file].

Whitaker, J. O., & Hamilton, W. J. (1998). *Mammals of the Eastern United States*. New York: Cornell University Press.

Wolff, J. O., & Guthrie, R. D. (1985). Why Are Aquatic Small Mammals So Large? *Oikos, 45(3),* 365-373

Woltz, H. W., Gibbs, J. P., & Ducey, P. K. (2008). Road crossing structures for amphibians and reptiles: Informing design through behavioral analysis. *Biological Conservation, 141*(11), 2745-2750.

Yanes, M., Velasco, J. M., & Suárez, F. (1995). Permeability of roads and railways to vertebrates: The importance of culverts. *Biological Conservation, 71*(3), 217-222.