A TEMPORAL ANALYSIS OF ELK MOVEMENT IN RELATION TO WASHINGTON'S TRANSPORTATION INFRASTRUCTURE

by

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ABSTRACT

A Temporal Analysis of Elk Movement in Relation to Washington's Transportation Infrastructure

Molly Tyler Sullivan

Many studies show that roads negatively affect wildlife, but many questions remain unanswered, such as exactly *how* roads influence species like elk (*Cervus elaphus*) (Montgomery et al. 2013). This often makes mitigation measures difficult to design and implement. However, to offset consequences of roads, mitigation techniques including wildlife crossings have been built into roads to facilitate wildlife movement. In partnership with the Washington State Department of Transportation, this study used data from the combination of motion-triggered cameras deployed around three underpasses in Washington State, Washington State Patrol Collision records, Washington State Department of Transportation Carcass Removal Information and locations of three elk in the Upper Snoqualmie Valley fitted with GPS collars to understand how existing infrastructure may facilitate wildlife movement. I compiled and statistically analyzed this information to understand whether different light levels, seasons and traffic volumes affect elk movement through underpasses below grade, elk-vehicle collisions at grade, and elk movement in relation to Interstate 90. Ultimately I discovered that elk used underpasses, and elk were involved in collisions on highways most frequently at night when traffic volumes were typically low. Since elk are normally most active during dawn and dusk, the observed patterns suggest that another factor may be influencing elk movement near roads, causing a shift from their normal behavior. Elk used underpasses most frequently during the fall and summer, likely in response to heightened activity during the mating and growing seasons, though the seasonal patterns of collisions were less well defined. Additionally, elk demonstrated a highly correlated albeit non-linear relationship between average distance to the road and light level according to varying traffic volumes. Despite available habitat on either side of the highway, collared elk remained close to the road but rarely crossed it. However, underpasses studied did reveal their effectiveness in allowing safe passage below the highway. This should be considered in future studies and transportation projects aiming to understand best practices for ameliorating effects of roads on wildlife movement, especially those intending to reduce habitat fragmentation and collisions between humans and elk. How well best practices focused on reducing collisions between humans and elk translate to other wildlife should be the basis of further study.

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Chapter 1: Literature Review

Introduction

Roads and transportation infrastructure span a large part of the United States, with public roads alone accounting for over 6.3 million km (Forman et al. 2003). This allows for settlement of remote areas, availability of goods, and communication. Such roads are an integral part of the development of the United States. However, with this large network of roads continually growing across the landscape, its negative impacts must also be analyzed, especially for wildlife. Wildlife evolved in specific habitats, none of which originally included such extensive human-made barriers. Therefore conflicts between wildlife and transportation infrastructure are growing. Despite our extensive roadway system in North America, only in the past few decades have researchers examined the negative impacts associated with the barriers that roads present to wildlife. Therefore this literature review begins with a brief overview of the history of roads and road ecology. Then I discuss current knowledge of negative impacts of roads for wildlife, and mitigation techniques and methods for evaluating road-crossing success. With an understanding of the challenges that roads pose to wildlife and how wildlife managers employ current mitigation measures, specific case studies will be analyzed. Because collisions with elk (*Cervus elaphus*) are frequent and highly detrimental in Washington State, I will focus on this species. Specifically, studies involving elk and transportation infrastructure will be discussed, as well as the lack of sufficient monitoring of the temporal aspects of elk movement. In conclusion, despite the growing body of research dedicated to road ecology, it will become clear that much more work needs to be conducted before we fully understand the effects of roads.

Roads: Their History and Evolution

A historical background of road and highway systems in North America is important for understanding road ecology and the various impacts of roads on wildlife. Therefore, a brief overview of the history of the road system in the United States is presented here. Road systems are important for most societies to function and communicate properly. In fact, roads have been integral parts of many societies for thousands of years, ranging from footpaths for humans, to dirt roads for moving armies and supplies, and finally to paved roads for motorized vehicles (Forman et al. 2003). Roads have similarly taken various shapes and sizes across the United States.

Though some paths were in place before European settlement, most current roads take their shapes from roads designed over 100 years ago (Forman et al. 2003). These early roads were concentrated in the eastern United States and spread outwards to export extractive resources. Therefore, most early roads were smaller, following the contour of the land (Forman et al. 2003) or game trails used by animals for movement and migration.

By the early 1900s, railroads had expanded rapidly across the US, and dominated most modes of transportation leaving little interest in road building (Forman et al. 2003), except near farmlands to haul grain. As automobiles became more common, roads quickly transformed from dirt, to oiled gravel, to asphalt (Forman et al. 2003).

Roads were heavily used in World War I to transport goods made in factories (Forman et al. 2003). After the war, the building of roads surged, due in large part to the implementation of the gas tax. In 1916 the U.S. Congress created the Federal-Aid Highway Program bringing with it the creation of state highway departments. By World War II suburban areas were common, and household cars used to transport people to and from these areas became a necessity. The resulting interstate highway program was created as a solution for the expanding presence of automobiles, trucks, and military strategies. As of 1991 due to the Intermodal Surface Transportation Efficiency Act, the responsibilities of roads were passed to local government authorities instead of federal agencies (Forman et al. 2003). Therefore, the myriads of roads today are owned by many different entities.

It is impressive how quickly roads spread across the US. In just over a century the entire landscape was drastically altered to include the vast network of highways and roads. New roads continue to be built, and existing roads continue to be widened (Forman et al. 2003), accommodating the nation's growing population and transportation needs. With the sharp transition from a once wide-open landscape, it is easy to imagine that animals evolving over thousands of years in such areas would find the new changes in the landscape difficult to maneuver.

The combination of a quickly growing road network, increasing human population size, and the fact that most roads followed the same paths of least resistance that many migratory animals utilize has proven to be literally lethal to wildlife. Though the negative influences of roads on wildlife were not initially taken into account, a new field of study has formed in the past few decades to address the many concerns that roads cause: road ecology, which will be further discussed in detail (Forman et al. 2003).

Road Ecology

Road ecology studies the influences and relationships of roads on surrounding environments and organisms (Forman et al. 2003). Road ecology can be focused on small-scale issues, such as a segment of road and its impact on one species, or road ecology can focus on large-scale issues, like the impediment of gene flow in animals across a road-divided landscape. Road ecology can even be addressed on a global scale, due to the vast network of roads stretching across the globe. Roads are somewhat ironic because though they connect people to almost anywhere on Earth, roads also drastically segregate many wild animal populations (Forman et al. 2003). Overall the diverse field of road ecology has grown in the past few decades and now focuses on important and prevalent issues (van der Ree et al. 2011) on many scales.

Road ecology is an extremely interdisciplinary field, requiring knowledge of: hydrology, microclimates, wind, weather, vegetation, biodiversity, wildlife, landscape ecology and habitat fragmentation (Forman et al. 2003). My thesis will focus on aspects of wildlife biology, specifically wildlife movement and wildlife-vehicle collisions (WVCs).

The US supports many herds of large mammals, and when these animal habitats overlap with human presence, problems like WVCs can occur (Forman et al. 2003). Instances of road-kill have been documented since the 1920s, with injury to humans driving further interest in reducing these occurrences (Forman et al. 2003). Applications of road impacts mitigation really began in the 1960s when bridges were constructed in France to allow games species safe travel over highways (Bielsa and Pineau 2007). Since then Europe has set many precedents for road ecology spurred by stringent motorist safety laws (Forman et al. 2003). In the United States in the 1970s, several wildlife overpasses were built in Utah and New Jersey and much research on deer and highways was conducted (Carbaugh et al. 1975). Florida gained prestige in the road ecology community in the 1980s and 1990s after building 23 underpasses, widening bridges for water movement purposes, and reducing instances of WVCs involving the endangered Florida Panther (Forman et al. 2003). The extensive collaboration of different entities, amount of funding, and public involvement focused on reducing vehicle-caused-panther-mortalities illustrates the interdisciplinarity of road ecology.

Studies in road ecology tend to focus on the most noticeable and costly effects of roads: WVCs and habitat fragmentation. Therefore, many experiments and projects since the 1990s have focused attention and research towards these areas. Road ecology issues have since been highlighted at international conferences, and the number of peer-reviewed papers that appear in scientific journals is growing (Forman et al. 2003). Most research, as evaluated by Taylor and Goldingay (2010) has been conducted in North America (51%) and Europe (25%) with an emphasis on mammals (53%), showing a distinct bias in this growing body of literature. Still in its infancy, road ecology has far-reaching implications for many disciplines. Therefore its gain in momentum needs to continue and expand into even more sectors so that studies can move beyond asking basic questions, and begin understanding the dynamic processes that make up this interesting field. After basic knowledge is acquired, more effective mitigation and planning processes can occur, thereby lessening the tension between overlapping human and wildlife habitats.

Effects of Roads on Wildlife and Humans

Scientists and transportation agencies are trying to gain a better understanding of the vast consequences of transportation infrastructure on wildlife, though only in the past few decades has serious thought been given to this problem. It is important to note that though roads take up a small portion of space on a landscape due to their linearity, their effects are startlingly disproportionate as they permeate far into adjacent landscapes (Jackson 2000, Frair et al. 2008). In fact, up to 20% of land mass in the US may be considered "road-effect zones" (Forman and Alexander 1998). Increasing distance and width of roads in addition to more people has led to an incredible loss in landscape connectivity, and remains a leading cause of habitat fragmentation (Beckmann and Hilty 2010). Roads and highways cause many issues for wildlife, though the extent and severity is different for each species and each population. The negative effects of roads include: economic costs, road mortality in the form of WVCs, habitat loss, habitat alteration, road avoidance and affinity, landscape connectivity and fragmentation, barrier effects and human access/exploitation. Each of these will be discussed subsequently in further detail.

Economic Costs

The overlap of human and animal habitats results in costly consequences. Such consequences include WVCs in the US that annually result in ~200 human fatalities, 29,000 human injuries and over $1 billion in property damage (White 2007). Other estimates are even higher, including one in 2007 in the US where over $8 billion in vehicle damage occurred as the result of 1 to 2 million accidents involving large mammals (Beckmann and Hilty 2010). Given the severity and costs of WVCs, it is in the best interest of states and motorists to reduce instances of collisions. Therefore, though roads have many other negative effects as listed and explained below, most states and agencies seek to reduce WVCs because of the impacts on human life and wildlife-related deaths, and the financial impacts.

Road Mortality: WVCs

Over 1 million vertebrates are killed on roads every day in the US (Lalo 1987). Road-associated mortality can have significantly detrimental effects on certain wildlife populations (Jaeger et al. 2005). It is important to understand that while other forms of vehicle-related crashes have remained relatively stable or in some cases declined, WVCs continue to rise (Huijser and McGowen 2010), with a doubling in fatal animal-vehicle collisions (AVC) since just 1990 (Sullivan 2011).

Several factors likely contribute to this upward trend including: 1) Increasing deer populations, 2) Increasing road traffic (Huijser and McGowen 2010), or 3) Suitable habitat adjacent to roads (Gunson et al. 2011). Washington State recorded at least 14,969 deer collisions and 415 elk collisions between 2000-2004 (WSDOT 2013a). Overall, an obvious increasing trend exists in WVC occurrences (Hughes et al. 1996). Road mortality rates are far higher than natural rates of mortality, and potentially pose serious threats to different species of vulnerable wildlife (Ciuti et al. 2012).

Though current estimates for collision mortality are already substantial, actual collisions are likely much higher due to selected data limitations. Road-kill is one way of enumerating WVCs, though it remains only a portion of the cumulative effects that roads have on wildlife (Forman and Alexander 1998). Limitations to using road-kill estimates include the fact that: 1) Many collisions and carcasses are not reported (WSDOT 2013a), 2) Some animals die out of sight of the roadway, and are therefore not seen (Prosser et al. 2008), 3) The time between death and pickup is often substantial (Prosser et al. 2008), 4) Maintenance crews are not required to report species picked up 5) Some species are incorrectly recorded or misidentified 6) Many systems do not categorize by species, but rather by general groupings and 7) Records only include state-maintained roads (WSDOT 2013a). Given these limitations, it is likely that actual numbers of wildlife mortalities are much higher than currently reported, as found in other studies (Teixera et al. 2013). Other equally important, yet sometimes ignored effects of roads are listed below.

Habitat loss

Roads have a direct effect on landscapes in the form of habitat loss. Not only do roads change habitat directly where the actual road is located, but the habitat adjacent to the road also subsequently changes (Forman et al. 2003). Roads and the impacted surrounding habitat, or edge, fragment once continuous landscapes which can negatively influence wildlife species differently according to their behavioral responses (Beckmann and Hilty 2010). Direct habitat loss from the 6.25 million km of public roads in the US is substantial, not including ongoing efforts to lengthen and widen existing roads. In addition to the overall loss of habitat, roads fragment landscapes causing edge effects that can extend anywhere from 10 to 100s of meters away from each road. Because of this, few places in the US lack the influence of roads in some way (Ament et al. 2008). Therefore, roads change landscapes not only through the physical placement of the road causing direct habitat loss, but also through habitat alternation due to edge effects, as will be explained below further.

Habitat Alteration

Roads can cause landscape changes, leading to increased or decreased habitat quality for surrounding wildlife. Roads sometimes increase surrounding habitat quality by creating additional habitat, or allowing certain species to move and detect prey more easily (Forman et al. 2003). For example, additional microhabitats like perches or nesting space are created along roads for birds (Forman et al. 2003). Additionally, excess nitrogen along roadways can facilitate some plant growth and subsequent insect populations. In fact, many roadsides that are regularly maintained result in high-quality habitat suitable for many species (Forman et al. 2003). For example, grazers may be attracted to medians that are planted with nutritious grasses or shrubs and maintained regularly. Therefore, although roads can sometimes improve surrounding habitats, the net effect of attracting wildlife to roadsides is problematic.

More often roads result in decreased habitat quality. For example, increased impermeable surfaces lead to more runoff, and contamination of adjacent habitats (Coffin 2007, Jackson 2000). Such impermeable surfaces also lead to increased concentrations of chemicals like heavy or harmful gases like carbon dioxide and ozone (Coffin 2007) that can negatively impact wildlife dependent on contaminated resources. The noise and unnatural light from roads can also influence wildlife negatively (Jaeger et al. 2005). Existing plant communities can be altered, either due to runoff or the introduction of invasive species (Forman et al. 2003). Therefore, not only do roads divide once contiguous landscapes, they also have far-reaching effects extending into their adjacent environments. These effects often influence the behavior of animals residing in habitat adjacent to roads, causing either an attraction to, or avoidance of, the road.

Road Affinity and Avoidance

Because of the resulting increased or decreased habitat quality that roads produce, many species respond differently to road presence. Increased habitat resulting in vegetation near roads can attract ungulates and small mammals, which are often hit by vehicles (Forman et al. 2003). Resulting road kill attracts scavengers such as eagles, coyotes, bears, and wolverines (Forman et al. 2003), which may also increase the likelihood of mortality in these species as well. In contrast, realizing that many predators avoid roads, moose for example, take advantage by giving birth closer to roads, increasing calf survivability (Berger 2007). More often, however, roads deter animals, effectively isolating species that require large tracts of land. Many migratory species like ungulates move long distances between summer and winter ranges to avoid harsh conditions and find scarce resources (Beckmann and Hilty 2010). The added difficulty of moving across roads is challenging for many species. Additionally, some species, especially predators, find the noise and light from cars disturbing and avoid roads and surrounding habitats altogether (Jackson 2000). Overall, a high density of existing roads in an area can exacerbate animal road affinity or avoidance, creating a distinctive faunal assemblage in road-associated habitats. As further explained below, addition of new roads continues to fragment landscapes, reducing overall habitat connectivity which can be detrimental to animals that are strongly influenced by roads.

Landscape Connectivity and Fragmentation

Landscape connectivity is an important factor in maintaining animals' basic needs, and when fragmentation occurs, many negative effects on wildlife are observed. Landscape connectivity is the ability of a landscape to provide animal passage and for other large-scale ecological processes to occur (Knaapen et al. 1992). Many mobile species require access to various habitats to meet their needs. Barriers to this movement result in increased mortality rates, decreased fecundity, smaller populations and decreased viability (Forman et al. 2003). When landscapes are fragmented it makes it difficult for species to repopulate following declines or maintain access to resources (Forman et al. 2003). Overall reduced landscape connectivity is especially detrimental to species requiring ample foraging area, species that disperse to establish new home ranges, for species that migrate (Forman et al. 2003) or for species and populations that exhibit metapopulation structure (Beckmann and Hilty 2010).

Habitat fragmentation reduces landscape connectivity, which imposes many effects on wildlife. Specifically habitat fragmentation results when a continuous habitat is divided into differently sized patches (Hilty et al. 2006). Since species have different habitat requirements, fragmentation affects organisms differently. For example, Brown-headed Cowbirds thrive in fragmented habitats because they can easily find passerine nests to lay their eggs in, much like a parasite (Donovan et al. 1997). However, some species like the Spotted Owl can only survive in large continuous landscapes (Lamberson et al. 1994). In fact for rare species habitat fragmentation is a substantial factor in population decline (Forman et al. 2003). So, while habitat fragmentation can create suitable habitat for some species, more often it results in less available, lower-quality habitat that has been detrimental to many vulnerable species.

Habitat fragmentation is a widely studied phenomenon, and it is a key component in the field of island biogeography (Hilty et al. 2006). Studies based on Island Biogeography Theory demonstrate that larger islands contain more species, islands closer to the mainland are more diverse, small islands are more prone to species extinctions, and islands near the mainland will have lower rates of species extinction (Hilty et al. 2006). Landscapes that are fragmented by roads are often likened to islands. Larger fragmented landscapes found closer to one another usually contain more species, and have more diversity, though current research shows that some landscapes can be linked together via corridors to conserve biodiversity (Hilty et al. 2006). However as landscapes become more fragmented and the area available to wildlife becomes smaller and farther apart, species may become prone to extinction. Wildlife isolated to small islands, or very fragmented landscapes are not as likely to persist because of lack of resources and lack of gene flow. Much like islands, these landscapes fragmented by roads can pose serious barriers to wildlife movement. Ultimately, roads impact population isolation, and potentially play a huge role in the negative effects of fragmentation and resulting barrier effects for wildlife.

Barrier Effects

Barrier effects resulting from the presence of roads are often difficult to see, and are therefore poorly understood (Forman et al. 2003). Speciation is one such effect, resulting in the evolution of new species following the isolation of subpopulations. This isolation can also lead to inbreeding depression, resulting in the continuation of less viable genes and the production of weaker populations of animals (Forman et al. 2003). Roads can also affect individual animal behavior (Forman et al. 2003) though more study should be dedicated to this area.

Specifically, roads can cause animals to change normal behaviors such as mating, birthing, and migration. These behavioral changes can also be attributed to increased human presence. Roads allow human access into once isolated areas, and this human presence can act as a barrier for animals, which will be explained below. Overall, these lesser-seen but equally important effects of road barriers can affect populations greatly.

Human Access/Exploitation

The main purpose of roads is to allow human access into certain areas, which also allows for human exploitation into previously isolated areas. Human presence alone can deter animals, along with the added competition of harvesting resources, changing the functionality of the landscape, introducing non-native species and even increasing hunting pressures (Jackson 2000, Bonnot et al. 2013). Animals are subject to the pressures that anthropogenic alterations have on the landscape, and roads greatly facilitate such rapid change and human colonization.

As demonstrated above, roads greatly influence natural landscapes and resulting wildlife habitats. Few positive ecological effects of roads exist as most contribute to the reduction of habitat quality and increased conflict between humans and animals. Knowledge of these negative effects has resulted in the creation and implementation of many mitigation techniques. These mitigation techniques serve to reduce wildlife mortality on roads, and better connect landscapes (Forman et al. 2003), which is important because the increasing road network in the US will likely only exacerbate the aforementioned effects.

Mitigation Techniques

Understanding issues in road ecology is a complex process, making the design of mitigation techniques diverse. Since transportation infrastructure not only presents a barrier to individual animals, the issue must be understood on a larger scale (Jackson 2000) and analyzed for higher order effects as well (van der Ree et al. 2011). The initial construction of roads and highways serves as only the beginning to the issue of fragmentation (Jackson 2000). The addition of longer, wider roads increases habitat fragmentation and exacerbates problems with wildlife (Jackson 2000).

Transportation agencies must now mitigate for negative impacts to wildlife and humans caused by both old and new roads. Without a proper understanding of the impacts that roads have on wildlife, roads and highways were placed in unsuitable areas for wildlife. Now that thousands of miles of roads cover vast stretches of the globe, it is necessary to both understand how to build better infrastructure for wildlife movement for the future, as well as deal with existing infrastructure. Mitigation techniques often involve changing infrastructure, or altering motorist behavior or animal behavior, or both (Glista et al. 2008, Clevenger and Ford 2010). Therefore, besides planning, collecting data and implementing proper road designs (Clevenger and Ford 2010), the following techniques attempt to mitigate the impacts that roads and highways currently pose on wildlife: constructing species-specific crossing structures, fencing, lighting, road removal, altering motorist behavior, and evaluating road-kill hotspots. Each of these mitigation methods will be discussed in sequence.

Crossing Structures

Several types of wildlife crossings exist, intended to allow wildlife movement between segregated habitats (Clevenger and Ford 2010). Wildlife crossings are widely cited as an appropriate mitigation technique, though few studies have actually provided solid evidence of their effectiveness (Beier and Noss 1998). In general, crossings above or below roadways provide connections between habitats for animals thereby reducing WVCs and increasing motorist safety (Clevenger and Ford 2010). It is important to recognize that using crossing structures to connect fragmented landscapes is dependent upon targeted species and the surrounding environment (Clevenger and Ford 2010). Since each wildlife crossing structure is unique and costly, it is necessary to fully understand the effectiveness of this expensive mitigation strategy. Finances often dictate the extent of mitigation measures, so that many effective measures are rarely implemented due to associated costs (Glista et al. 2008). The following are several types of crossing structures that help mitigate the negative influences of roads on wildlife.

Overpasses

Wildlife overpasses are large structures, usually spanning roadways instead of entire landscapes, allowing large- and medium-sized wildlife species access to adjacent habitats (Clevenger and Ford 2010). Some overpasses are used strictly for animals, while others accommodate humans as well. These overpasses allow animals to cross over highways, and are usually very effective when combined with fencing to keep wildlife off the adjacent road. While construction costs are relatively high, overpasses effectively link ecological processes across a landscape, acting as “landscape connectors” (Forman et al. 1997). Overpasses can be designed for a specific species to maximize effectiveness. Some of the most recognizable and impressive overpasses designed for wildlife mitigation are located in Banff, Canada. Banff is a leader in designing and implementing wildlife crossing structures, with the building of over 24 crossing structures during the twinning process of the Trans-Canada Highway (TCH) (Ford et al. 2010).

Bridges

Landscape bridges are just one type of overpass. They tend to be large, with the ability to provide connectivity for many animals (Clevenger and Ford 2010). Landscape elements like vegetation can be included in some types of bridge designs to help facilitate acceptance and movement of animals underneath or across the structure (Clevenger and Ford 2010). Notable wildlife bridges include those built along I-75 for the Florida Panther (Jansen et al. 2010), and those located in Banff National Park along the TCH (Ford et a. 2010).

Canopy Crossings

Canopy crossings are used in forested habitats for arboreal or semi-arboreal species (Clevenger and Ford 2010). They can include the use of ropes or cables across roads. These innovative structures are especially important for animals like squirrel gliders (*Petaurus norfolcensis),* in areas where road length exceeds their gliding abilities (van der Ree et al. 2010). Without habitat connectivity measures, these animals are effectively isolated to fragmented canopy stands.

Viaducts

Viaducts are elevated roadways usually used for wetland habitats (Clevenger and Ford 2010, Jackson and Griffin 2000). Because viaducts span valleys or gorges, they help keep hydrological flows intact, and can be a low impact solution to habitat connectivity needs in riparian areas (Clevenger and Ford 2010, Jackson and Griffin 2000). Viaducts are typically more open structures that incorporate vegetation, so they are especially functional for animals found in riparian areas (Jackson and Griffin 2000).

Underpasses

There are many different types and sizes of underpasses, serving a range of species. Underpasses differing in size and allowance of water flow can provide targeted movement for animals and humans (Clevenger and Ford 2010). They can be large enough to naturally mimic terrain preferred by certain animals, though often these effective structures are expensive to implement (Glista et al. 2008).

Culverts

Culverts used as wildlife crossings are typically used by small- and medium-sized animals residing in riparian habitats (Clevenger and Ford 2010). Dry platforms, walkways and ramps are all forms of modifications that can be applied to culverts to further increase wildlife use (Clevenger and Ford 2010). Different types of culverts such as drainage culverts, upland culverts and oversized stream culverts can be used in different habitats (Jackson 2000). Typically, pipe culverts are used by amphibians, in contrast to box culverts that are used by more species because they only conduct water during heavy rains (Glista et al. 2008). Though many culverts are not big enough for larger animals, and can become blocked and require regular maintenance, they are often an economical solution (Glista et al. 2008).

Other Mitigation Techniques

Fencing

Fencing has been a key mitigation strategy for many years. Fencing is often considered a critical component to helping funnel animals into crossing structures. A study in Banff National Park showed that implementation of fencing resulted in an 80% reduction of WVCs (Clevenger et al. 2001). Whether or not fencing acts as a complete barrier in keeping animals off roads, it has its limitations too. Fencing is expensive and requires regular maintenance. Additionally, it usually only inhibits larger animal passage, it can cause an "end-of-the-fence" problem, and animals can become trapped in areas if they accidentally get around the fencing (Clevenger and Ford 2010). These "end-of-the-fence-problems" occur when animals can easily enter the roadway once the fence stops. Increased amounts of WVCs at these locations are good indicators of this problem. This can be mitigated using additional techniques, like using fencing to funnel animals into underpasses (Clevenger et al. 2001). Animals trapped inside of fences are especially dangerous, so steel swing gates, hinged metal doors, earthen ramps and jump-outs are commonly used to reduce negative effects of fencing (Clevenger and Ford 2010). Despite end-of-the-fence issues, some areas have shown reduced costs associated with fencing by only using partial fencing (Ascensao et al. 2013). They showed nearly the same level of effectiveness with 75% fencing as 100% fencing previously had, though such results should be interpreted and implemented with caution.

Lighting

Since many WVCs occur at night, with some areas reporting that over 80% of collisions with deer occur from sunset to sunrise (Carbaugh et al. 1975, Reed and Woodard 1981), it is important to have mitigation measures directed at different levels of light. Though the effectiveness of highway lighting to decrease accidents is not completely understood, it has long been thought of as an expensive but possibly useful way to increase motorist visibility (Reed and Woodard 1981). Overall, Reed and Woodard (1981) did not show that crossings-per-accident were different when lights were on or off, though motorists did reduce their speed when deer simulations were placed in view. In fact, Reed and Woodard (1981) found that more deer crossed the highway after it was illuminated. It is still possible that different intensities or types of light might influence wildlife deterrence from highways (Blackwell and Seamans 2008). Overall, lighting has not been shown to effectively reduce WVCs.

Road Removal

Since roads are one of the main impacts on wildlife and habitat, some restoration techniques have focused on removing roads altogether (Switalski and Nelson 2011). Researchers in the Northern Rocky Mountains discovered that black bears were found more frequently on closed roads, or recontoured roads, suggesting that this might be an effective habitat restoration mitigation measure.

Nonstructural Methods

In areas where crossing structures are not feasible, other nonstructural methods can be utilized to deter animals from using roads and adjacent habitats if needed. Methods include: olfactory repellents, ultrasound, road lighting, population control, and habitat modification (Glista et al. 2008).

Motorist Behavior

Changing motorist behavior is just as important as wildlife management in many environments. Though several studies have tried to decipher the exact implications of speed limits, amount of light, and traffic volumes, much is left to discover. Overall the use of signs, speed bumps, reduced speed (high-speed traffic is one of main causes of WVCs), wildlife crossing signs, and flashing lights have all been implemented to make drivers more alert (Glista et al. 2008). Human behaviors may be important, too, as Neumann et al. (2012) suggested due to evidence showing that collisions likely happened in more human-modified areas with higher traffic speeds. Indeed traffic speed is important, especially as drivers tend to increase speed at night (Ramp et al. 2006) when many animals may be closer to roads.

Road-kill Hotspots

Areas with high rates of collisions and road-kill are often chosen as a priority for mitigation placement. This is indeed a powerful tool to understand WVC impacts on a large-scale, but care should be extended when interpreting the effects on individual populations. Today's road-kill estimates may not truly represent the extent of impact for some species, especially for populations that have been declining for decades due to WVCs (Eberhardt et al. 2013). Overall, using road-kill hotspots is an important technique, but more parameters should be included depending upon specific species.

Effects of roads on landscapes, humans, and animals are substantial. Therefore, many mitigation measures ranging in cost and effectiveness are employed to combat problems caused by overlapping human and wildlife habitats. Understanding animal needs and the type of surrounding habitat is crucial for implementing the most effective mitigation measure. In fact, evaluating effectiveness remains an important component to project success measurements, though this is difficult to quantify.

Evaluating Mitigation Strategies

Because wildlife crossing structures are usually unique to a specific landscape, target species and purpose, measuring effectiveness can be challenging. However, some of the techniques listed below may be used to help researchers gain a better understanding of the overall effectiveness of corridors.

Visual Observation

Some early studies of road ecology in general used human observation to detect wildlife presence. This technique is time-intensive, expensive, and could cause animals to avoid areas where humans are present. Though visual observation is a good way to understand animal behaviors at crossing structures, this technique is now infrequently used (K. McAllister, personal communication, 2013).

Track Pads

Track pads can be used to detect wildlife moving through structures (K. McAllister, personal communication, 2013). They can be set up for days at a time with little cost, and are relatively non-invasive. Identifying animals from track pads requires someone skilled at reading tracks to decipher differences among species and count individuals. This technique is often used in tandem with other identification methods.

Cameras and Video

Motion-triggered cameras are now frequently used to detect animals moving through structures (Jackson 2000, Bissonette and Rosa 2012). Cameras record time and temperature in addition to images of wildlife. These cameras require little maintenance and are mostly non-invasive, making them ideal for observational purposes. Some older cameras may produce a red flash or click when photos are taken, possibly frightening animals. Most animals do not notice the cameras, especially if they are deployed effectively. For species with non-unique pelage, these cameras cannot be used to determine number of animals using structures, only frequencies. For other species like jaguars, which can be identified based on unique patterns of pelage, cameras can be used to identify individual animals non-invasively and therefore provide density estimates of relatively elusive animals (Soisalo and Cavalcanti 2006). Motion-triggered cameras are often used in tandem with other methods. Drawbacks of cameras include difficultly in placement to accurately record warm-blooded animals, and vandalism (Jackson 2000). One of the most important constraints of these cameras is the resulting data, which often exhibits a lack of variance estimates, which is critical for applying diverse statistical analyses of such data (Bengsen et al. 2011). Regardless, these cameras are a good way to monitor structure use and activity.

DNA Analysis

Hair snags using barbed wire are used to gain genetic information on species or numbers of individuals using crossing structures (Clevenger and Ford 2010). For example studies in Banff National Park (BNP), the North American epicenter of road mitigation techniques (Sawaya et al. 2013), have used hair snags. Using hair snag DNA analysis, they found that crossing structures allowed sufficient demographic connectivity for bears in BNP. Of these bears, almost 20% of each population used the crossing structures. Hair snag analyses are now being used for bears and cougars in Washington State (R. Beausoleil, personal communication, 2013). This technique usually involves stringing barbed wire perpendicular to an animal's path. As an animal moves over or under the wire, hair becomes caught on the barbed wire. Hair tufts can later be gathered and further sampled in a lab. This technique is minimally invasive.

VHF and GPS Collars

Other monitoring techniques include use of very high frequency (VHF) radio collars and global positioning system (GPS) radio collars to track individual animal movement despite their relation to the structure (Montgomery et al. 2013, Gagnon et al. 2007a, Gagnon et al. 2007b). Attaching collars to animals requires finding animals, immobilizing them, and fitting collars onto them, which is relatively invasive. Collars typically cost several thousand dollars and can be used anywhere from days to years, depending on battery life and size which must be appropriately sized for the animal depending upon its mass. VHF collars rely on a signal that is emitted from the collar that a researcher must find. GPS collars use satellites to triangulate an animal's position that can be downloaded at different frequencies to a computer. Having continuous data on animal locations allows researchers to see what types of habitats animals reside in or move through, in comparison to when such animals move through crossing structures. Collars are often used in road ecology studies with wildlife.

Many monitoring techniques like motion-triggered cameras and GPS or VHF radio collars are now being implemented by several different agencies. Overall, some monitoring techniques are outdated, while others continuously improve. Often times using a combination of techniques proves adequate. Regardless of monitoring technique, today's interagency collaboration indicates that issues in road ecology are finally being addressed. Even a decade ago, road ecology was not widely recognized. Now almost one third of US agencies have employed some type of wildlife mitigation measure (Clevenger and Ford 2010). In the past solid knowledge about mitigation techniques was rarely based on research (Forman et al. 2003). One study used a survey to assess national park management units' level of concern about roads. Results showed that many respondents thought that WVCs affected populations of wildlife, though there was little systematically gathered supporting evidence (Ament et al. 2008). The field of road ecology has much room for improvement in both conducting research systematically, and disseminating results and information to the public. No doubt as wildlife management, technology, transportation, and intercollaboration increase in efficacy, advances and knowledge in this field are sure to emerge.

These advances will help agencies create solutions for both humans, and specific types of wildlife. Elk are one wildlife species that many transportation agencies try to effectively manage because collisions can be highly detrimental, sometimes resulting in human fatalities. Therefore, general information regarding elk, as well as more in-depth studies examining the effects of roads and safe crossing structures will be further discussed.

Elk

In the US, and especially in Washington State, elk are of special interest in studies regarding road ecology. Elk are commonly studied because: 1) Their populations are abundant, 2) They migrate and occupy a wide range of habitats, 3) Their large body size poses a significant threat to motorists if hit, and 4) They are a managed game species of high value to the hunting community. Collisions with elk can be expensive due to the level of physical damage and sustained injuries. Therefore, many studies in the US focus on elk, with the goal of reducing WVCs and their associated costs and dangers.

Elk were once widespread across North America before European settlement, with estimates around 10 million (Rocky Mountain Elk Foundation 2013). About 1 million elk remain in the western US with a few herds in the east and south. Elk are divided into six subspecies: Rocky Mountain, Roosevelt's, Tule, Manitoban, Merriam's, and Eastern though the latter two are extinct (Rocky Mountain Elk Foundation 2013). Despite this reduction in historic numbers, the current estimate of elk in Washington State, which is limited to Rocky Mountain and Roosevelt's subspecies, is over 60,000 individuals (USFWS 2013).

Many elk in Washington State are highly mobile. They often travel long distances for foraging or to mate. Depending on whether a herd is resident or migratory, some elk travel long distances due to the effects of seasonal fluctuations on available forage resources (Hobbs et al. 1981). Many herds migrate to find suitable habitats containing grasses, forbs, shrubs, tree bark or twigs (Rocky Mountain Elk Foundation 2013). Studies show that elk dedicate most of their time to feeding with peak intensities around dusk and dawn, shifting only for seasonal fluctuations (Green and Bear 1990). Such important foraging needs and physiological changes also depend on the energy requirements of elk in terms of seasonal activities including mating and calving (Fancy and White 1985). For example, bull antlers grow and harden by late summer, allowing for proper defense by the rut in the fall. Males may move through habitats to gather and protect harems of females and calves, resulting in newborn calves the following summer (Rocky Mountain Elk Foundation 2013). As previously discussed, elk are very mobile species, and occupy many different types of suitable habitat in the US, anywhere from rainforests to desert valleys.

Elk are impressive creatures, were named "Wapiti" by Native Americans for their white rumps, and can weigh anywhere from 225 kg (females) to 315 kg (males) with newborn calves weighing up to 16 kg (Rocky Mountain Elk Foundation 2013). Besides the sustenance that their harvested meat provides, these animals have long held spiritual importance for many Native American tribes. Today elk hunting draws considerable attention and is a critical asset to wildlife departments that benefit fiscally from purchased tags. These animals are an important part of many different cultures and agencies for various reasons, making WVCs with elk particularly detrimental.

All in all, the combination of sizeable populations, high degrees of mobility and large body sizes makes elk relatively dangerous to motorists. Though many recent studies of traffic flow and effects of roads have given rise to a body of literature focused on techniques for monitoring wildlife-roads effects, data addressing elk-road effects lack the diversity to effectively answer critical questions. Much more research is necessary to understand exactly how roads affect elk, and how different populations and individual elk respond to anthropogenic disturbances generated from roads. To date, productive but only limited study has been dedicated to the topic of elk movement in relation to roads, and elk behavior in relation to mitigation efforts like underpasses.

Elk in Relation to Roads and Underpasses

Many studies show that roads negatively affect wildlife, but many questions remain unanswered, such as exactly *how* roads influence elk (Montgomery et al. 2013). Several studies have attempted to isolate factors that negatively influence elk movement near roads. Other studies examine elk movement at wildlife crossing structures to gain a sense of influential factors. A comparison of these factors between elk movement at roads and underpasses helps researchers understand whether or not underpasses alleviate some disturbances generated from roads.

Factors Affecting Elk Movement near Roads

Identifying and understanding the negative effects of roads that inhibit elk movement is a primary concern. So far, influential factors including road type, season, gender, traffic volume and temporal shifts in behavior have been studied. For example, Montgomery et al. (2013) examined elk over many years to better understand how elk responded to roads according to road type, season and sex finding that road type did in fact influence elk space use, with differences according to seasons and sex. Overall elk home ranges were situated more closely to roads without public vehicle traffic, and avoided primary and tertiary roads with high traffic levels. Females and males avoided such active roads at different times of the year. Males avoided busy roads in the summer when vehicle traffic peaked, and females avoided busy roads during spring and autumn in conjunction with calving and mating. Therefore, though high traffic volumes remained relatively consistent throughout the year, elk still avoided primary and tertiary roads, suggesting that they did not habituate to the disturbance. Interestingly, researchers found that when traffic levels increased, elk would more likely use habitat that had a visual barrier to even primary roads, though they tended to avoid habitat that was clearly visible from roads. This could be a result of increased hunting pressures in areas with greater road access, or a result of calving and subsequent caring and protection of their young (Montgomery et al.

2013). Interestingly the results showed a possible coping mechanism for elk in relation to roads, though the negative influence of roads was clear.

Gagon et al. (2007a) also studied how traffic affected elk distribution and crossings in relation to highways. Using traffic recorders and GPS relocation points, they found that elk moved away from roads during times of high traffic. When traffic levels subsided, elk moved closer to roads with suitable habitat quality. This could be explained by the possible habituation of elk to road disturbances, or due to the high quality riparian meadow habitat adjacent to the road. Because elk still utilized habitat close to roads, the likelihood of WVCs increased. Though some studies show higher rates of WVCs during periods of high traffic (Gunson et al. 2003) possibly due to migration needs, low traffic collisions could be a result of high quality habitat near roads. Therefore, Gagnon et al. (2007a) also clearly shows the negative influence of roads on elk.

Many studies show that elk behavior changes at night, and recognize the need for temporal analysis of elk use (Montgomery et al. 2013, Gagnon et al. 2007a). Millspaugh (1999) showed that elk move closer to roads with suitable adjacent habitat when traffic volume is lower at night. Other studies have also shown that elk move closer to roads at night, and may exhibit diurnal movement patterns when close to low-traffic roads (Ager et al. 2003). Studies of similar animals like moose have also shown temporal adjustments due to anthropogenic disturbances (Neumann et al. 2013). Grizzly bears in Canada were also shown to adjust their behavior, moving nearer to and across roads with less traffic at night (Northrup et al. 2012). As demonstrated above, during times of heavy traffic volume, roads created a barrier for many animals. Since this barrier might cause animals to change the timing of some activities, additional research analyzing temporal aspects is needed so that transportation planners can implement effective mitigation techniques, and so that drivers may be more aware of the possibility of wildlife presence on roadways during certain times.

Factors Affecting Use of Wildlife Structures

To offset consequences of roads, several wildlife crossings have been built into roads to facilitate wildlife movement. Important factors including traffic volume, temporal shifts in behavior, and adjacent habitat quality have been the subjects of research at underpasses. Gagnon et al. (2007b) stresses the importance of studying the influence of traffic on wildlife at underpasses, especially because previous studies have hypothesized that high traffic volumes completely inhibit animals crossing highways (Mueller and Berthound 1997). Therefore, understanding if this factor also inhibits elk use of underpasses is critical in determining their effectiveness for alleviating negative effects of roads. Gagnon et al. (2007b) studied how traffic affected elk use of an underpass and found that higher levels of traffic did not deter elk use of such structures. While traffic has been shown to discourage elk from moving over highways, it does not seem to influence elk use of underpasses, thereby increasing the effectiveness of the underpass for linking habitats once segregated by roads. Though some animals were repelled at times possibly due to noise from larger vehicles, most animals traveling in herds followed the lead elk through the underpass (Gagnon et al. 2007b). Overall this study suggests that high volumes of traffic known to deter elk from crossing highways do not influence elk use of underpasses (Gagnon et al. 2007b, Dodd and Gagnon 2011). Another study demonstrated that elk typically used underpasses at night when traffic volume was lower (Servheen et al. 2003). Similarly Dodd et al. (2006a) found that traffic influenced elk crossings, with more crossings occurring at lower traffic volumes. Since traffic volume changes throughout the day, some studies have focused on the temporal patterns of elk movements at these underpasses.

A temporal understanding of elk movement is important to understand because it may account for observed behavioral shifts. Looking specifically at underpasses, Servheen et al. (2003) found that ungulates tended to move through more frequently during crepuscular periods (dawn and dusk). Since elk are most active during dawn and dusk normally, this indicates that elk are using underpasses within their normal hours of activity. However, any deviation from their normal activity pattern could indicate that animals are changing their behavior to accommodate for selected anthropogenic disturbances found at these underpasses.

Seasonality and associated quality habitat is another important factor in determining effectiveness of underpasses. Researchers found that high passage rates in spring and summer might be attributed to the forage found in riparian meadows (Gagnon et al. 2007b). If elk are attracted to high quality riparian habitat at underpasses, it may influence passage rates and mask disturbances that would make elk otherwise avoid areas near roads.

Though abundant wildlife crossings are lacking where elk can be studied, the few studies that have examined these interactions have proven valuable. At a basic level, researchers understand that roads can influence habitat use (Lyon 1979, Jones and Hudson 2002), isolate populations influencing genetics (Forman et al. 2003), and can cause WVCs (Forman et al. 2003). Researching how mitigation measures, such as safe crossing structures, can alleviate some of these pressures is important. In fact, current studies have demonstrated that roads do in fact negatively influence wildlife movement, and that wildlife structures intending to alleviate this are effective. These recent research efforts provide a beginning understanding of elk behavior in response to this infrastructure. More research needs to be conducted to obtain a finer-scale resolution of temporal elk movement so that we may predict when elk use these structures and when they might avoid them. With this knowledge scientists and transportation agencies can continue refining ways to better provide safe crossing opportunities for elk.

Literature Review Summary and Thesis Research Questions

The advent and expansion of roads in the US was a sharp transition for the landscape, resulting in fragmented habitats that often harm wildlife or cause conflicts with humans. Though roads are necessary for human transport and obtaining resources, many negative effects exist on wildlife. These include economic costs, road mortality in the form of WVCs, habitat loss, habitat alteration, road avoidance and affinity, landscape connectivity and fragmentation, barrier effects and human access/exploitation. Hence, a myriad of mitigation techniques including overpasses, underpasses, culverts, bridges, canopy crossings and viaducts have been designed and implemented to allow wildlife movement over or under roads safely.

Current research needs include addressing animal behavior at structures already in place. Research regarding species that pose serious safety risks like elk because of their high mobility, large body size, and abundance in Washington State should be prioritized. Knowing exactly when elk use safe crossing structures will help researchers not only evaluate current underpass effectiveness, but will also aid in developing mitigation techniques refined to focus in the problem time intervals. Though much knowledge is known about when elk are typically most active, monitoring their activity in relation to underpasses and roads is important to understand what influences these safe crossing opportunities have on elk. If activity levels at underpasses are not the same as normal activity patterns, this may suggest that elk are responding to some anthropogenic influence caused by roads. Therefore, using multiple data sources regarding elk, underpass use, and collisions the following research aims to:

1.) Summarize and analyze temporal patterns based on light levels of elk use of underpasses and collisions with vehicles at three underpasses in Washington State
2.) Summarize and analyze seasonal patterns of elk use of underpasses and collisions with vehicles at three underpasses in Washington State
3.) Analyze the influence of traffic levels on elk use of underpasses and elk-vehicle collisions near three underpasses in Washington State

Prominent gaps exist in the literature, which hinders understanding about the temporal and seasonal influences of safe crossing structures and elk movement. Therefore, using a combination of data sources, I seek to address a substantial portion of these gaps, and discover how and when elk use safe crossing opportunities, when they do not, and how other factors, such as traffic volume may influence this. Ultimately the information I have analyzed will be given to and used by the Washington State Department of Transportation (WSDOT) so that the needs of elk may be better understood and addressed in current retrofitting projects and future construction efforts.

Chapter 2: Analysis of Elk Movement in Relation to Transportation Infrastructure at Grade and below Grade

Introduction: Roads and Wildlife

Conflicts arising from the dual needs of human transportation and wildlife habitat requirements can be dangerous, even lethal (Hilty et al. 2010). In fact, today it is likely that roads with vehicles surpass hunting as the largest source of vertebrate mortality (Forman and Alexander 1998). Despite this fact, transportation infrastructure continues to increase, especially the construction of roads for human mobility, transportation of goods and resources, military operations and economic development even though it is increasingly understood to negatively impact wildlife (Forman et al. 2003). In response to these increasingly obvious impacts, the field of road ecology has emerged as an important area of study to gain a better understanding of how roads affect wildlife, which species are most at risk, how roads impact wildlife habitat connectivity, and how to begin mitigating for the harmful effects on wildlife (Forman et al. 2003). Habitat fragmentation and wildlife-vehicle collisions (WVCs) are two of the biggest consequences of roads often studied in this discipline.

The vast road network in the US increasingly fragments habitats and landscapes. Gunson et al. (2011) concluded that as roads continue transecting landscapes, avoidance of natural areas and wildlife species is increasingly difficult, especially since up to 20% of landmass in the US may already be considered “road-effect zones” (Forman and Alexander 1998). Habitat fragmentation associated with roads dissecting natural landscapes is especially dangerous when large mobile animals enter roadways. Collisions between large animals and vehicles often result in injury or death to humans and wildlife, and also contribute to property damage.

In the US, the number of collisions with animals is concerning, and often results in substantial property damage. Collisions with animals are estimated to be around 300,000 per year according to national crash databases (Huijser et al. 2008). Due to issues with collecting and reporting this information, this estimate is likely conservative. Actual numbers of collisions between vehicles and large animals are estimated to orders of magnitude greater than 1-2 million per year, most of which do not result in serious injury (95.4%) (Huijser et al. 2008). The resulting 26,000 injuries and 200 deaths per year are a significant issue, especially considering total WVCs continue to rise in comparison to all other types of collisions (Figure 1).

For other wildlife-related collisions, regardless of injury or death, property damage may be substantial. Collisions with larger animals typically result in greater property damage, between $3,000-4,000 for elk (*Cervus elaphus*) collisions (Huijser et al. 2008). Overall, nationwide WVCs are estimated to cost > 8 billion dollars each year when factoring in vehicle repair costs, medical costs, towing, law enforcement, monetary value for the animal, and carcass removal and disposal.

To reduce costs to humans and wildlife from WVCs, mitigation efforts have been developed. Mitigation measures including underpasses are necessary to minimize associated injury, death and property damage resulting from WVCs. Studies have shown that underpasses may provide safe crossing opportunities for wildlife like elk (Barrueto et al. 2014, Dodd et al. 2006b, Dodd et al. 2007, Gagnon et al. 2007a, Gagnon et al. 2007b). To better understand how existing infrastructure may facilitate wildlife movement, my research focused on elk movement at grade and below grade in relation to three underpasses in two geographically separate areas in Washington State. Specifically, I conducted a temporal analysis examining when elk are most likely to cross at grade and be hit by vehicles, and when they are most likely to use underpasses. Understanding patterns of when elk cross at grade or below grade will help researchers better predict WVCs, and design mitigation measures to prevent future issues.

This study uses existing underpasses in Washington State to analyze elk movement according to light level, seasonality and traffic volume. Ultimately the goal of my research is to gain further understanding of the impacts of roads so that mitigation efforts might help make our roadways safer for multiple species.

Study Area

For this study, I drew data from individual elk from two of Washington State's elk herds managed by the Washington State Department of Fish and Wildlife (WDFW). One of the herds studied, the North Rainier Herd, was located in North Bend in the Upper Snoqualmie Valley. The second site located between

Randle and Packwood in the Cowlitz River Valley supports elk from the South Rainier Elk Herd. Elk were studied at three different underpasses in the Upper Snoqualmie Valley and the Cowlitz River Valley, and along I-90 and US-12 highways within 20-32 km of each underpass, as subsequently explained (Figure 2).

Upper Snoqualmie Valley Site

North Bend is located in the Upper Snoqualmie Valley in Western Washington, 50 km east of Seattle (latitude: 47.493831; longitude: -121.786247) in the Cascade Range foothills. Average annual precipitation is 137.5cm. With less than 5,000 residents, this town in King County is made up of many private agricultural holdings as well as some housing, subdivision and commercial buildings all of which are connected by Interstate 90 (Henceforth, I-90) (US Census Bureau, Spencer 2002). I-90 is the longest interstate highway in the US, spanning from the East in Boston, MA to Washington State, at its westernmost extent, and remains the only interstate highway to span the Cascade Mountain Range in northwest Washington. This route has been an important part of travel in Washington since before the original Oregon Trail Pioneers, when Native Americans favored it as a cross-mountain trail. Today I-90 is the most heavily used transportation corridor to connect eastern and western Washington for recreational, commercial, and commuter trips.

I-90 runs to the south of the town of North Bend with three lanes of traffic in each direction, and an annual average daily traffic (AADT) volume of about

29,000 vehicles (WSDOT 2013b). It parallels the South Fork of the Snoqualmie River, crossing over it in several places. The river provides ample riparian habitat for wildlife in Snoqualmie Valley. Forests adjacent to I-90 near North Bend are dominated by western hemlock (*Tsuga heterophylla*), Pacific silver fir (*Abies amabilis*), mountain hemlock (*Tsuga mertensiana*) and Douglas fir (*Pseudotsuga menziesii*). Mount Si and Rattlesnake Ridge are nearby, adding to the region's diverse habitat, suitable for a myriad of species. Megafauna species such as black bear (*Ursus americanus*), black-tailed deer (*Odocoileus hemionus columbianus*), bobcat (*Lynx rufus*), cougar (*Puma concolor*), and elk are known to reside in this area. Historical elk presence in the Cascades has been debated, with some believing that elk did not exist prior to introductions in the 1900s (Bradley 1982). Other records support elk presence in Washington before European settlement, with Puyallup Tribe members actively managing elk habitat with fire near Mount Rainier (Schullery 1984).

Regardless of their historical presence, Rocky Mountain elk were transplanted from Yellowstone National Park in Montana to the Cascades in the early 1900s. One elk herd examined in this thesis is part of the North Rainier Elk Herd found on Game Management Unit (GMU) 460, located in the Snoqualmie valley. According to the Washington State Elk Herd Plan produced by WDFW, little population data are available for the Snoqualmie valley sub-herd of the North Rainier Elk Herd. WDFW personnel estimated that the Snoqualmie valley sub-herd comprised 125 elk in 1989, with numbers increasing to 175 elk in 2000. Today, elk population numbers in the Snoqualmie valley sub-herd are recovering well. According to the Upper Snoqualmie Valley Elk Management Group's 2012 research and management committee annual report, the population estimate for elk in the valley was 428 individuals in 2011. Nonetheless, this elk population still faces some challenges.

Elk in the North Rainier Herd are subject to several sources of mortality including predation, hunting, and roads. Predation by cougars and black bears occurs on both adult and juvenile elk. Additionally, both state and tribal hunting continues in this area. Road kill is the third major source of mortality for elk in this area. I-90 poses a barrier to elk, though some elk have been seen to utilize habitat on both sides of the I-90, making crossings over the highway that are dangerous to motorists as well as elk (Starr, 2012). Several WVCs and carcass removals are reported in this area every year.

In an effort to understand how roads affect wildlife, and how animal-vehicle collisions may be reduced, WSDOT began monitoring wildlife use of underpasses in 2010. Specifically on I-90 in the vicinity of North Bend, several underpasses are equipped with motion-triggered cameras to capture animal movement around and through transportation infrastructure (Figure 3). Each camera monitors a bridge underpass adjacent to the South Fork of the Snoqualmie River. For this study, I used data from cameras located at mileposts 31.6 and 38 to collect information related to elk movement. Cameras were located within 16km of each other along this stretch of I-90 south of North Bend.

North Bend Site (Milepost 31.6)

The underpass along I-90 at milepost 31.6 has a total of four motion-triggered cameras. I-90 crosses over the South Fork of the Snoqualmie River in the form of a steel and concrete bridge built in 1976. Surrounding habitat includes riparian areas, and mixed use residential. Two cameras on the east side of the river are located along a heavily used recreational trail that sees little wildlife use. The other two cameras are located on the west side, with a view of the bridge's abutment and pier. Both cameras are within 100m of the river. Tall chain link fence (1.8m) exists along each side of the river, but parts of the fence are in disrepair, and wildlife can be found on both sides of the fence.

North Bend Site (Milepost 38)

The underpass along I-90 at milepost 38 has a total of four cameras. I-90 crosses over the South Fork of the Snoqualmie River in the form of a concrete and steel bridge as well, built in 1976, with cameras monitoring both the east and west sides of the divided highway. Surrounding vegetation includes riparian habitat. Tall barbed wire fence (0.9m) exists near the structures along the associated riprap. The fence, in many areas, is in disrepair.

Cowlitz River Valley Site

Randle and Packwood are small towns located in Lewis County in western Washington, connected by US-12 in the Cowlitz River Valley. US-12 is a 2-lane undivided highway running east and west across Washington. Annual AADT is ~

3,000 vehicles. Cora Bridge, a steel and concrete bridge, was built in 1948 to span the width of the Cowlitz River where US-12 crosses over. Though not originally intended to facilitate safe animal movement, several species are observed to move safely under the highway via use of this underpass.

The area surrounding Cora Bridge is made up of riparian habitat, with occasional flooding during severe storms. Average annual precipitation is 152.4cm (Huang et al. 2002). The U.S. Forest service owns much land in this area, in addition to state and privately owned industrial forestland. Many small private holdings are found along the Cowlitz River where the terrain is mostly flat. Residential and agricultural developments are common. Though the area adjacent to Cora Bridge is dominated by grassland habitat, the larger area supports western hemlock, Pacific silver fir, and mountain hemlock. This area also supports megafauna including black-tailed deer in addition to domestic livestock (Huang et al. 2002).

Elk from the South Rainier herd occur in this area between Randle and Packwood, located within the Packwood GMU 516. Roosevelt elk once dominated this area, but their extirpation by the 1900s led to translocations of Rocky Mountain Elk from Yellowstone National Park to increase elk numbers. Population estimates from 1996-1998 surveys show elk numbers ranging from 28 to 95 individuals in the GMU 516. Surveys have differed dramatically between years, with the estimate in 2009 for the entire South Rainier Herd at about 1,000 individuals. Sources of elk mortality are mostly attributed to hunting, though habitat modification and collisions with vehicles are also potential sources of mortality. The underpass at Cora Bridge is monitored by WSDOT for wildlife use with three motion-triggered cameras (Figure 4). Two cameras are located on the east side of the river, and one on the west side of the river. Tall grasses and Himalayan blackberry dominate this area. Easy access to the Cowlitz River also allows for considerable use by humans. No fencing exists along the highway, and the cattle fence surrounding the adjacent property is in disrepair. Elk have been observed jumping over it easily.

Methods

Origination of the Study

In response to WSDOT's Habitat Connectivity policy directive stating the agency's role in protecting ecosystem health, Julia Kintsch and Dr. Patricia Cramer were hired by WSDOT to conduct a study that ranked a sample of existing bridges and culverts in Washington State on their ability to allow wildlife passage. Using motion-triggered cameras at culverts and bridges, Kintsch and Cramer (2011) developed a Passage Assessment System (PAS) allowing the Transportation Department to understand where roads facilitated or prohibited animal movement. Using this tool, WSDOT continues to monitor many bridges in Washington. My research is a continuation of those monitoring efforts, and borrows many methods in terms of set up, analysis, and one study site based on this research report's parameters. The data used in my study were collected and analyzed from motion-triggered cameras deployed around underpasses, collision records from Washington State Patrol Officers, the WSDOT carcass removal database, GPS locations from elk collared by the Upper Snoqualmie Valley Elk Management Group (USVEMG), and traffic volumes from WSDOT permanent traffic recorders.

Identifying Underpasses for Analysis and Camera Set Up

Highway segments that had high to medium amounts of road kill were initially used to identify problem areas in terms of WVC rates. With a general awareness of wildlife-vehicle issues and known crossing structures, bridges were then further chosen within a 320km distance of office headquarters to ensure that cameras could be checked regularly. Bridge selection was also based on: appropriate dimensions sizeable enough to allow large mammal passage, occurrence within a riparian area, and known elk presence. Bridges were then outfitted with 3-4 motion-triggered cameras. According to Kintsch and Cramer (2011) cameras were initially positioned at each end of the structure so that animal approaches and passes could be recorded. Since each site is different, modifications were made to the camera deployment. In North Bend along I-90 at milepost 31.6 two cameras were placed in the median facing east and west. One monitored a pedestrian trail and the other monitored the river. Under the eastbound lanes of traffic two cameras were positioned to capture animals moving past the abutment and along a dike that flanks the river. Along I-90 at milepost 38 cameras were located under the off-ramp and westbound lanes of traffic, monitoring the area adjacent to the river and the abutment. Due to large areas beneath bridges, cameras could not always be safely deployed at the ends of each structure. Therefore cameras were placed in positions under bridges that allowed researchers to assess whether or not an animal passed through the structure.

The motion-triggered trail cameras (ReconyxPC85, ReconyxHC600, ReconyxPC900, and Bushnell) were either disguised in steel utility boxes or bolted to trees. Utility boxes were set into a concrete foundation of about 18-27kg with a protruding bike cable that attached, by padlock, to the camera. The front portion of the box was also secured with a combination padlock. Cameras in trees were enclosed in metal boxes bolted from the inside to the tree. The camouflaged faceplate on the box was secured using a combination padlock. Cameras were also equipped with a passcode. Despite safety precautions taken, theft and vandalism occurred periodically at other camera locations in the area, which made us particularly cautious with security measures. Fortunately, none of the 12 cameras used in this study were destroyed or stolen during the length of this study.

Camera Data and Elk Activity at Underpasses

<u>*Data Collection*</u>

Cameras were serviced every four weeks. Servicing included changing all batteries (either 6C batteries or 12AA batteries) and data cards (holding 2 to 16 GB). Cameras were also checked for correct settings: date and time, 3-5 pictures were taken when motion was detected, with no delay in between pictures, pictures were taken day and night, and trigger speed was high. Cameras were also changed and swapped if poor performance or malfunctions occurred.

I downloaded and processed data from memory cards in the office. Each series of images was reviewed and recorded. Information recorded included: date, temperature, time (in Pacific Standard Time) the animal was first observed, time (in Pacific Standard Time) the animal was last observed, species, age, gender if identifiable, total number of animals, whether the animal went through the structure or not, as well as anything of note such as number of antler points or if a cow wore a collar. Detections were recorded in 30min intervals. Therefore, if an animal was seen grazing in front of the camera for one hour, it constituted 2 separate detections unless the individual animal was clearly identifiable, in which case it counted as a single detection. Individuals were recognized when possible, and total numbers within 30min increments were enumerated. Any species identification challenges were brought to several biologists for discussion. Data were kept for every image on each camera in extensive spreadsheets.

Data Organization

Data from Microsoft Excel spreadsheets were then compiled until a full annual cycle of monitoring was obtained. I then selected elk records for further analysis. Furthermore, only records indicating that an elk actually passed through a structure were used. If an animal was detected by the camera, but did not actually cross through the structure, it was not considered a passage, and was not included in the further analysis.

> According to the Transportation Research Board of the National Academies A crossing structure [is] defined as a new or retrofit passage over or below roadway or railroad that was designed specifically or in part, to assist in

> wildlife movement. Culverts and bridges already in place when fencing was installed to lead animals to these pre-existing structures were not considered crossings.

Based on this definition, the structures analyzed in this study are not considered crossing structures because they were not built specifically for wildlife use, nor have they been retrofitted to accommodate them. However, because elk do use them to cross under roads and provide safe passage, they will be referred to as “underpasses,” “safe crossing opportunities,” or “crossing structures” in this study because of their ability to facilitate wildlife movement, albeit unintentionally.

At each underpass, several cameras monitored the structure, so duplicate occurrences were identified and deleted to avoid over-estimates of elk occurrence at each structure. To do this, I compared MS Excel records of images on each camera. If an elk was detected by both a camera and its partner camera (or the camera located at the opposite end of the structure) within a 15min time frame, the occurrence was deleted from one camera’s data. Therefore, when data were compiled in total for each site from the individual cameras, elk detections were not over-enumerated. Though total elk numbers were recorded, a detection was considered a single occurrence regardless of the total number of individuals. Since elk are often found in herds, to ensure independence due to herd mentality only single occurrences were analyzed. In the context of this study, an “occurrence” or “detection” refers to a single event in which the camera detected elk movement regardless of the total number of individuals. In reality, the number of actual crossings made by individual elk is a much larger number

(Figure 5).

Categorizing Detections

These occurrences were then categorized according to light level. It is widely reported that elk are crepuscular, meaning they are most active at dusk and dawn, or rather during twilight (Green and Bear 1990, Wichrowski et al. 2005). According to the National Oceanic Atmospheric Administration and the US Navy, twilight occurs, “Before sunrise and again after sunset… during which there is natural light provided by the upper atmosphere, which does receive direct sunlight and reflects part of it toward the Earth's surface (NOAA 2013)”. Many factors, including atmospheric state and weather conditions, affect duration of twilight. Furthermore, twilight can be broken down into three categories: civil, nautical and astronomical. According to NOAA, civil twilight occurs when the sun is 6° below the horizon. This state usually allows sufficient light to see, and is commonly referred to as twilight. There are two other stages of twilight, nautical and astronomical. Nautical twilight, according to NOAA, occurs when the sun’s center is 12° below the horizon (Figure 6). Finally, astronomical twilight occurs when the sun is 18° below the horizon. Before astronomical twilight in the morning and after astronomical twilight in the evening, the sky is completely dark. Since twilight depends upon sunrise and sunset, sunrise according to NOAA is defined as, “The time at which the first part of the sun appears above the horizon in the morning,” and sunset is defined as, “The time at this the last part of the sun disappears below the horizon in the evening (NOAA 2013).” Dawn and dusk refer to these periods of twilight as well. Therefore the term “dawn” shall reference the entire time from when the sun is 18° below the horizon, to sunrise. The term “dusk” references the time from sunset to when the sun is 18° below the horizon. The term “twilight” will refer to these periods of dawn and dusk.

Using these definitions of light, a formula was created in MS Excel to analyze each elk crossing in terms of relationship to sunrise, sunset, and twilight time periods. Data on sunrise, sunset, and twilight were obtained from NOAA for North Bend and Morton (data were not available for Randle or Packwood specifically, so the nearest location at a similar latitude was chosen) (NOAA 2013). Data were then converted, consisting of every day’s times for sunrise, sunset and twilight periods from 2008-2013. As amount of visible light differs slightly each day due to Earth’s rotation around the sun and axis tilt, sunrise, sunset and twilight were calculated to the minute for each day and categorized as: dawn (includes time beginning at astronomical twilight up to sunrise), day (includes time from sunrise to sunset), dusk (includes time from sunset to astronomical twilight), and night (includes time from the end of astronomical twilight after sunset to the beginning of astronomical twilight before sunrise). A multiple step IF/THEN, VLOOKUP, and INDEX:MATCH function was written to categorize each camera detection of elk into one of the previous light categories to the specific day and minute of each light level. Seasons were categorized into sub-equal three-month intervals as Fall (September, October, and November), Winter (December, January, and February), Spring (March, April, and May), and Summer (June, July, and August) using a MS Excel function.

Light Level

Data were first summarized to detect patterns and frequencies of elk movement at all three underpasses. A nonparametric analysis of variance using a Wilcoxon/Kruskal-Wallis Rank Sum Test and Post-hoc analyses using the Wilcoxon Method were used to understand if underpass use differed according to light level. A chi-square goodness-of-fit test with a William's correction for small sample sizes was used to determine if elk crossed under bridges more or less than expected during a certain light level. Due to differences between sites, I-90 and US-12 were separately analyzed with chi-square tests and non-parametric analysis of variance tests using a Wilcoxon/Kruskal-Wallis Rank Sum Test and Post-hoc analyses using the Wilcoxon Method.

Light Level and Traffic Volume

A parametric analysis of variance using log-transformed traffic values was used to analyze differences in traffic volumes at different light levels in addition to analyses using the Wilcoxon/Kruskal Wallis Rank Sum Test and a Post-hoc analysis using the Wilcoxon Method. Further analyses of underpasses along I-90 and US-12 were conducted separately using Wilcoxon/Kruskal Wallis Rank Sum Tests and a Post-hoc analysis using the Wilcoxon Method to examine the differences in mean ranks of traffic volume during elk detections according to light level.

Seasonality

MS Excel functions were used to identify each underpass use into different seasons, and then these data were summarized. A chi-square goodness-of-fit test with a William's correction for small sample sizes was used to determine if elk crossed under bridges more or less than expected during a certain season. Further analyses using chi-square goodness-of-fit tests revealed differences between use of underpasses by elk during various seasons. Therefore, a nonparametric analysis of variance using a Wilcoxon/Kruskal-Wallis Rank Sum Test and Post-hoc analyses using the Wilcoxon Method were used to understand which mean ranks according to seasons differed from one another combining sites when appropriate.

Elk-Vehicle Collision Data

Data Collection

Data were obtained from the WSDOT Collision Database by performing a query, and selecting for "elk" and the years "2008-2013". Accidents involving animals and vehicles were recorded and reported by Washington State Patrol if the damage was at least $700. Therefore, collisions resulting in minor damage or injury were not included. Reports included time of collision, type of animal, any evident human injury, surface conditions, and other facts regarding the collision. These reports were then narrowed down from the state level to an appropriate proximity to both study areas within 32km east or west of camera placement under bridges along either I-90 or US-12.

Light Level

Formulas in MS Excel were applied to collision records, categorizing each into the appropriate light level. A nonparametric analysis of variance using a Wilcoxon/Kruskal-Wallis Rank Sum Test and a Post-hoc analysis using the Wilcoxon Method were used to understand which light levels differed from one another.

Light Level and Traffic Volume

Effects of traffic volume at each site were analyzed using a Wilcoxon/Kruskal-Wallis Rank Sum Test followed by a Post-hoc analysis using the Wilcoxon Method. Collisions along I-90 and US-12 were further analyzed according to light level separately using a Wilcoxon/Kruskal-Wallis Rank Sum Test followed by a Post-hoc analysis using the Wilcoxon Method. After failing to meet assumptions of normality, traffic data was log-transformed and a two-way ANOVA using site and light as independent variables and log-transformed traffic volumes during times of elk collisions as the dependent variable was performed (Table 4). This was followed by a Student-Newman-Keuls mean separation test to determine differences between traffic volumes at each site.

Seasonality

MS Excel functions were used to identify each elk collision into different seasons, and these data were summarized. A chi-square goodness-of-fit test with a William's correction for small sample size was used to determine if EVCs occurred more or less than expected during a certain season at each site. Then a nonparametric analysis of variance using a Wilcoxon/Kruskal-Wallis Rank Sum Test and Post-hoc analyses using the Wilcoxon Method were used to understand which seasons differed from one another along I-90 and US-12 separately.

Carcass Removal Data

Data Collection

I also obtained data from the WSDOT Carcass Removal Database. Road maintenance crews around the state often remove animals from the road, and record their findings on a PDA device selecting for species, age, and highway milepost number. Some maintenance crew members record road-kill by hand and these are sent to WSDOT headquarters and entered into the database manually. These reports likely represent a portion of the total number of actual collisions between animals and vehicles because not all carcasses are reported, some animals do not die directly on the road, and not all maintenance crew members record road-kill pickups. The reports that are generated are compiled and stored in the WSDOT carcass removal database. Records were obtained using a query for “elk” and years “2008-2013”. The database is updated periodically. Data was gathered and summarized for descriptive statistical purposes, especially for comparison to EVCs.

Telemetry Data

Data Collection

Data were also obtained from GPS collars on elk in the Upper Snoqualmie Valley. The USVEMG has deployed 13 GPS collars on female elk to understand their movements. Due to a partnership with WSDOT, GPS locations are made available for analysis in the form of MS Excel spreadsheets that include: date, time, number of fixes, GPS locations in latitude/longitude form, and positional accuracy. Female elk were captured and fitted with global positioning system (GPS) telemetry collars, LOTEK 4400S and 4400M (Lotek Wireless, Newmarket, Ontario, Canada) between 2010 and 2012. Clover traps were used to capture elk, with immobilization used as necessary with telazol/xylazine HCL with the reversal Yohimbine on hand. Biologists from the state and Muckleshoot Tribe, and a veterinarian handled captured elk (USVEMG 2010) (Starr 2013). Elk collar data ranges according to when elk were captured, how long their collars collected data for, how many fixes were scheduled, and survival of individual elk. I chose three elk from this dataset for this study expressly because each had a full year worth of fixes (from March 2011 to March 2012).

Geographic Information Systems and Spatial Statistics

Elk location data, in the form of latitude and longitude positions, were imported into ArcMap, and converted into North American Datum (NAD) 1983. I created a projection using the middle of the study area to minimize visual distortion since this area is close to the boundary between UTM Zone 10 and 11 (ESRI 2013).

Elk distance to the road was calculated using ArcMap's "near" tool. I then exported these distances, calculated in meters, to MS Excel. Each fix was categorized using a MS Excel function into light level, and traffic volume according to day and hour was assigned. As a precursor to analysis, I then compiled summary information including average distance to the road and number of fixes.

Light Level and Distance to I-90

A chi-square goodness-of-fit test with a William's correction for small sample size was used to see if the observed distances that elk were found to the road were different than the expected distances of elk to the road.

Distance to I-90 and Traffic Volume

A correlation function using a Pearson Product-Moment Correlation Coefficient was used to see if any correlation existed between average distance of elk to the road and corresponding traffic levels. Traffic volumes were log-transformed to normalize the data.

Traffic Data

Data Collection

WSDOT monitors traffic levels through use of permanent traffic recorders around the state. Traffic volume data was obtained for I-90 near North Bend and US-12 near Randle and Packwood by performing a query in WSDOT's internal database.

A permanent traffic recorder is located within 16km of North Bend. Since no permanent traffic recorder exists close to Randle or Packwood, I used the closest permanent traffic recorder that showed the same level of traffic to the Randle/Packwood area. Therefore, I performed a query using the years "2008-2013" to obtain annual average hourly traffic (AAHT) at the two study sites. Due to malfunctions or missing data from these permanent traffic recorders, some days lacked traffic data. Using an INDEX:MATCH function in MS Excel, traffic data was then linked to each camera detection, collision and GPS fix according to specific date and hour. Data were analyzed using Microsoft Excel, JMP, JMP Pro, and CoStats. Analyses assumed data were independent. However, efficiency of reporting collisions and carcasses varied, and was a source of uncertainty of unknown dimension. Data were screened for outliers and errors before analyses. Sample sizes differed between record strings, and those too small for adequate analysis were excluded.

Results

Camera Data and Elk Activity at Underpasses

Using data collected from cameras at one underpass along US-12 during 2012 and 2013, and two underpasses along I-90 during 2013, I found that elk used these structures 183 times with the highest levels of use documented at underpasses in the Upper Snoqualmie Valley (Figure 7).

Light Levels

Of the 183 safe crossing detections, most occurred during two of the four light categories, night and day (Figure 8). Elk use of underpasses significantly differed among light levels ($p<0.0001$). Post-hoc analyses revealed that the mean ranks of elk underpass use differed among all possible pairs of light level categories: between night and dawn, night and dusk, night and day, day and dawn ($p<0.0001$), dusk and dawn ($p=0.0036$), and between dusk and day ($p=0.0414$). Results also indicate that the observed values of elk use of underpasses differed from the expected values of elk underpass use during different light levels at the three study sites (*g-adjusted* $p=0.0032$, df=6) (Table 1).

The two underpasses in North Bend did not show any significant difference between expected and observed values of elk underpass use based on light levels ($\chi^2=0.2408$, df=3). Therefore, the data were combined. Since there was a difference between the three study sites, further analyses using the combined data from the two underpasses along I-90 were performed separately from the underpass at US-12 to understand the differences between sites on a finer scale.

Based on its mean rank, elk underpass use along I-90 underpasses differed among light levels ($p<0.0001$, df=3); use further differed between all light level category combinations ($p<0.0001$). The observed versus expected detections of elk underpass use at US-12 did not differ between years ($\chi^2=0.1401$, df=3). Elk underpass use along the US-12 underpass also differed based on light levels for both years of camera data combined ($p<0.0001$) differing between night and dawn, night and dusk, night and day ($p<0.0001$), day and dawn, dusk and dawn ($p=0.0040$), but not between dusk and day.

Light Level and Traffic Volume

Since the data failed to meet parametric assumptions, a 2-way ANOVA used log-transformed values of the dependent variable traffic volume to examine the relationship between light level and site according to traffic volume (Table 2).

Results reveal that the interaction between light and site was significant ($p<0.0001$, df=6). Additionally elk underpass use differed according to traffic levels during different light levels ($p<0.0001$, df=3) with the mean ranks of dusk and day, dusk and dawn, day and dawn ($p<0.0001$), and night and dusk ($p=0.0441$) differing from one another, though night and dawn ($p=0.6456$) and night and day ($p=0.4592$) did not differ. Since the underpass structures differ along I-90 and US-12, each was analyzed separately to understand finer-scale differences in response to traffic levels.

At the underpasses along I-90 in North Bend, traffic volume during the periods of elk detections differed significantly based on light level ($p<0.0001$, df=3). Specifically, the light categories of day and dawn, night and dusk, and night and day ($p<0.0001$) differed, but night and dawn ($p=0.9678$) and dusk and day ($p=0.5030$) did not.

Along US-12, the mean ranks of traffic volume during elk detections significantly differed according to light level ($p=0.0002$, df=3). Day and dawn ($p=0.0136$), dusk and dawn ($p=.0139$), night and day ($p=0.0016$) and night and dusk (*p*=0.0016) differed but night and dawn (*p*=0.3313) did not, nor did dusk and day since values were the same.

Seasonality

Using 183 detections, our research found that elk use of underpasses in summer and fall was twice the rate of spring and winter (Figure 9). Our results analyzing seasonal differences of elk underpass use revealed that elk used underpasses differently than expected according to season at the study sites (*g-adjusted p*=0.0013, df=6) (Table 3).

Analyzing the seasonal differences between the two underpasses in North Bend, I found that observed elk movement according to season differed from expected values at these structures (χ^2=0.0264, df=3). Observed values of elk use of underpasses according to season between the structure along I-90 at milepost 31.6 and the underpass along US-12 also significantly differed from expected values (χ^2=0.0006, df=3). Observed values of underpass use between the structure along I-90 at milepost 38 and the underpass along US-12 did not differ from expected values between seasons (χ^2=0.2802, df=3).

I found that elk use was different among seasons at the I-90 underpasses located at mileposts 31.6 and 38 (*p*<0.0001, df=3) between all possible season comparisons (*p*<0.0001), except for winter and spring because both had the same number of detections.

I also found that elk use differed among seasons using camera detections from the I-90 underpass located at milepost 38 and the US-12 underpass combined ($p<0.0001$, df=3). At both underpasses, elk use differed between all possible season comparisons ($p<0.0001$).

Elk-Vehicle Collisions

From 2009-2013, 540 elk collisions were recorded in Washington State, which averages to 108 elk collisions/year. Of these collisions, an average of 18% occurred within my I-90 and US-12 study areas, with some years accounting for fully over 25% of state-wide collisions (Figure 10). During the same 5-year time period, 695 elk carcasses were removed from state-maintained roads by WSDOT maintenance staff (Figure 11).

Light Level

Of the 99 collisions reported along I-90 and US-12 near underpasses, twice as many collisions occurred during night than any other light level category (Figure 12). On average, more collisions occurred along US-12 with 11 collisions/year in comparison to I-90, which averaged 8 collisions/year. Elk collisions differed among light level categories along the interstate highways in my study area ($p<0.0001$) with differences occurring between all possible comparisons of light level categories ($p<0.0001$).

Light Level and Traffic Volume

Traffic volumes associated with elk collisions differed among light level categories over the last five years at both study sites ($p<0.0001$, df=3). Specifically, I found differences between day and dawn ($p=0.0014$), dusk and day (*p*=0.0084), night and dusk (*p*=0.0228), and night and day (*p*<0.0001), but not between dusk and dawn (*p*=0.3122) or night and dawn (*p*=0.8951).

Because I-90 and US-12 vary in number of lanes and division of lanes by medians, they were further analyzed separately. Results indicate that collisions along I-90 occurred during different levels of traffic (*p*=0.0057, df=3) and between the light level categories of day and dawn (*p*=0.0057), dusk and dawn (*p*=0.0450), and night and day (*p*=0.0083), but there was no difference between night and dawn (*p*=0.2928), dusk and day (*p*=0.7104), or night and dusk (*p*=0.0937). Collisions with elk occurred during different levels of traffic along US-12 as well (*p*=0.0001, df=3) and between the light level categories of day and dawn (*p*=0.0139), dusk and dawn (*p*=0.0014), and night and dusk (*p*=0.0002), but not between night and dawn (*p*=0.0779), dusk and day (*p*=0.7261) or night and day (*p*=0.1126).

Light level and site were significantly related to traffic volume at the time that elk were struck (*p*=0.0000). However, the interaction term light × site was not significant (*p*=0.4874). Moreover, traffic volume when elk are struck on I-90 is significantly greater than traffic volume when elk are struck on US-12 and that traffic volume during the day when elk are struck is significantly greater than traffic volume when elk are struck at dusk, at dawn and at night (Table 5-6). Further, traffic volume at dawn does not differ significantly from traffic volume at night.

Seasonality

Of the 99 collisions reported along I-90 and US-12 near monitored underpasses, collisions were highest in the spring and fall, but occurred in all seasons (Figure 13).

An analysis of seasonal differences revealed that elk collisions differed from expected values of elk collisions according to specific seasons at the study sites (*g-adjusted* p=0.0110, df=3) (Table 7).

Elk collision levels along I-90 differed among seasons (p<0.0001) between all season pair combinations (p=0.0001). Elk collision levels along US-12 also differed significantly among seasons (p<0.0001) between all season pair combinations (p=0.0001) except between winter and summer since values were the same.

Telemetry

Using three elk, I found that each remained relatively close to I-90, though elk 1550 traveled farther on average (Table 8).

Light Level and Distance to I-90

Distances that elk were found from the road were different than expected distances according to light level (*g-adjusted* p=0.0012, df=6) (Table 9).

Distance to I-90 and Traffic Volume

Using elk distances to I-90 and corresponding traffic volumes, I observed only a weak ($r=0.0096$), non-significant ($p=0.6294$) relationship. Using the log-transformed values revealed a high degree of correlation between elk distance to road and traffic volume ($r=0.9942$). Though the two are correlated, the relationship is non-linear.

Discussion

This study showed that underpasses are a mitigation tool that can potentially redirect above-grade movement of elk and perhaps decrease the incidence of collisions between wildlife and vehicles. Light levels, seasons, and traffic volumes affected when elk used underpasses, when vehicles hit elk, and how close elk were found to at least one interstate highway. Based on diel light level categories, elk used three underpasses in Washington differently, though the most frequent usage occurred at night when traffic volumes were typically lower. This research also revealed that elk used underpasses in all seasons, but increased their use during seasons that typically correspond with increased movement, such as fall. Unsuccessful elk attempts to cross at grade resulted in several WVCs along I-90 and US-12 during the past five years. Though elk collisions occurred during all light levels, twice as many collisions occurred at night than any other light level category, when traffic levels were usually lowest. Collisions were more frequent during the spring and fall, when nutritional requirements and activity levels are typically heightened (Green and Bear 1990). Lastly, three elk with home ranges close to I-90 were shown to remain close to the highway. They were not found near the highway equally between all light levels, revealing a non-linear relationship to corresponding traffic volumes.

Therefore, this research demonstrates that I-90 in the Upper Snoqualmie River Valley and US-12 in the Cowlitz Valley pose a significant barrier to elk movement. Elk still cross at grade, as shown from collision and carcass removal data, but the few underpasses in these areas do serve to offset some local movement at all times of the day, year round. This suggests that the underpasses may serve as effective mitigation measures for the high amount of collisions occurring in these areas. However, additional fencing, jumpouts and more underpasses and overpasses in this area could serve to reduce collisions and further promote habitat connectivity in these hot spots.

Camera Data and Elk Activity at Underpasses

Light Level

I expected to observe more elk movement through underpasses during crepuscular time intervals since studies show that elk spend a majority of their time feeding, with peak activity levels during dawn and dusk (Green and Bear 1990; Wichrowski et al. 2005). I found that elk used underpasses during all light level categories differently, with most usage occurring at night (Figure 8). Elk also moved through these underpasses at various light levels differently than expected, with most use not occurring during dusk and dawn (Table 1). In this study elk do not use underpasses more frequently during their normal peak hours of activity at dusk and dawn like other studies have shown (Green and Bear 1990, Gates and Hudson 1983, Servheen et al. 2003). This suggests that some factor other than their normal behavior is driving their temporal use of these structures. Possible explanations for this nighttime-dominated use may be explained by human disturbance or temperature. Similar to this study, Barrueto et al. (2014) found that elk were sensitive to human activities, and altered their activity patterns in response. Elk may use habitat closer to the highway, including underpasses at night because of reduced human disturbance. Both study sites are located along rivers that have typically high human activity. Additionally, hunting occurs in both study sites, accounting for a large source of mortality especially in the South Rainier Herd. Elk may be more active near roadways at night in response to either human presence or hunting pressure.

Moreover, elk may use structures more during nighttime to conserve energy when daytime temperatures are elevated. Elk, like most species, attempt to gain the greatest caloric intake while minimizing energy expenditure (Charnov 1976). Elk are typically active when temperatures <15°C (Bleich et al. 2001), but bed down possibly to avoid higher temperatures during the day during warmer months. Because of this, elk may in fact alter their normal patterns of movement to take advantage of cooler temperatures at night and expend less energy while grazing, thus attributing to the high presence of elk at night.

Though the nighttime-dominated use of underpasses was unexpected, other factors including human disturbance or temperatures might be contributing to this behavior. Another factor, traffic volume, has also been studied recently and could be influential in explaining the high frequency of underpass use at night.

Light Level and Traffic Volume

Light level and underpass site had an interactive effect when examining when elk used underpasses at different light levels according to traffic volumes. More underpass use occurred at night, when traffic volumes were typically lower. Other studies have similarly hypothesized that low nighttime traffic volumes may be an important influence on elk underpass use (Servheen et al. 2003). The greater traffic volumes may inhibit elk crossings at grade, though this may be less of a deterrent for elk that use underpasses (Gagnon et al. 2007b, Dodd et al. 2009). In some cases, traffic volume appeared unrelated to underpass use (Gagnon et al. 2011), especially since some studies have showed that elk herds will follow a leader through an underpass, increasing the frequency of underpass use regardless of disturbances (Gagnon et al. 2007b). While elk detections at underpasses in this study occurred during all light level categories, elk were seen to use underpasses more frequently at night. Naylor et al. (2009) found that elk altered their normal activities in response to off-road recreation treatments, revealing that even recreational activities like mountain biking disturb elk. Therefore, elk in these study areas may be influenced by traffic volumes and associated visual and auditory annoyances. The results of this study suggest that elk in these study areas might still be shifting their normal patterns of behavior in response to some disturbance.

In summary, this study revealed much higher use of underpasses at night, in contrast to other studies showing elk use predominately during crepuscular periods. This dissimilarity might be attributed to other factors including human disturbance, temperature or traffic volume.

Seasonality

Ungulates perform different life functions according to season, and correspondingly change their behavior to meet their energy requirements (Fancy and White 1985, Jones and Hudson 2002). Since the rut, or mating season, for elk takes place during the fall, I expected to see more elk use of underpasses during the fall. While I did observe substantial use during the fall, elk used underpasses more during the summer in contrast to other studies (Montgomery et al. 2013) (Figure 9). However, elk were observed using underpasses during all seasons similar to previous studies (Gagnon et al. 2011) but several factors might explain the increases in summer and fall observed in this study including foraging to meet energy requirements, anthropogenic influences, migration or gender.

Ungulates synchronize activities with foraging opportunities to meet basic nutritional requirements (Gedir and Hudson 1999) which are often influential in establishment of home ranges (Anderson et al. 2005). Since forage changes in response to seasons, ungulate activity responds accordingly. Similar to my findings, other studies have also showed that elk forage more at night during the summer (Gates and Hudson 1983). During the summer, ample vegetation exists for elk to graze on, getting ready for the rut in the fall when elk seek mates and will travel long distances to find suitable ones (Craighead et al. 1973). Similarly, Gagnon et al. (2007b) found higher passage rates of elk during the summer and spring likely due to the quality forage found in riparian areas. Manzo (2006) also found that elk use riparian habitats near roads. Since the study sites used in this thesis are found in riparian habitats, high peaks of underpass use observed during the summer reflect this factor as well, whereas high usage during the fall may be attributed to the increased movement during the rut.

Anthropogenic disturbances are important in determining when elk are most likely to use underpasses. Ungulates have been shown to be sensitive to human-caused disturbances (Perry and Overly 1977, Lyon 1979, Rowland et al. 2000) and will increase their movements, which decreases their likelihood of survival (Cole et al. 1997). Hunting is a real pressure felt by both herds in these study areas (WDFW) and represents a large source of mortality for populations that may be legally harvested (Raedeke et al. 2002, McCorquodale et al. 2003). Since roads increase human access into areas, with Lyon and Burcham (1998) finding that fully one quarter of hunters' time is spent within less than 300m of a road, it is possible that elk respond accordingly to this pressure and increase their movement, causing a spike in underpass use during the fall.

Migration is also an important factor in seasonal use of underpasses. Levels of migration differ in both the North and South Rainier Elk Herds, ranging from individuals that migrate long distances to those that remain residents of an area. According to Moeller (2010,) many forms of elk migration exist, ranging from individuals that do not migrate, to those that migrate in response to forage, to those that move to entirely new habitats. Since many elk in the Cascades were transplanted in the 1900s from Montana, their seasonal movement patterns are extremely varied. Similar to other studies, the fewer numbers of elk that are seen during the spring and winter might be attributed to migratory elk (Dodd et al. 2007). Despite the fact that most elk observed in this study are thought to be resident herds, it is possible that some may migrate during different parts of the year.

Gender may also play a role in seasonal underpass use. Montgomery et al. (2013) found that elk were closer to roads during different seasons, with females avoiding busy roads during spring and autumn when their calves are typically born. Males on the other hand avoided busy roads during the summer time, when traffic levels are typically the highest. Though the data in this study are not gender specific it is possible that low levels of elk underpass use during the spring may be attributed to female calving, and their avoidance of roads.

Ultimately, season remains an important driving force of elk activity. In this study, we saw high frequency of elk use during the summer and fall. Though not consistent with all other studies, factors like forage quality, anthropogenic disturbances, migration and gender may be influential in seasonal use of underpasses by elk.

Elk-Vehicle Collisions (EVC)

Light Level

Using Washington State Patrol's records of vehicle collisions with elk, I found approximately 11 collisions with elk occurred along the US-12 site per year, as opposed to 8 per year along I-90 in North Bend (Figure 10). These collision records represent the absolute minimum number of road caused elk mortalities. Looking at carcass removal records for the same stretch of highway during the same years, there were more elk removed from roads that reported by collisions (Figure 11). Because elk are generally considered crepuscular in their activity, I hypothesized that collisions between elk and vehicles would occur more frequently during dusk and dawn. However, of the collisions in these study areas, twice as many occurred at night than any other light level (Figure 12) similar to other studies (Carbaugh et al. 1975). However, EVCs did occur differently at all light levels in contrast to other studies that showed collisions occurred more frequently during dawn and dusk (Dodd et al. 2006a, Haikonen and Summala 2001, Gunson et al. 2003). Therefore other factors such as driver reactions, habitat type and surrounding vegetation may influence patterns of EVCs in relation to light level.

Drivers are an important component of EVCs. Lao et al. (2011) found that speed limit and surrounding habitat type increased effects of animal-vehicle collisions (AVC). Using regression models to predict AVCs, Lao et al. (2011) found that drivers' responses became less effective with higher speeds, increasing significantly at speeds over 50mph. Since both I-90 and US-12 speed limits exceed 50mph, more collisions might occur due to high speeds either because of a driver's inability to react effectively or because elk cannot judge distance and speed accurately. Exacerbating the problem, drivers also tend to increase their speed at night (Barrientos and Bolonio 2009), especially if the road is straight (Gunson et al. 2011). Since most collisions along I-90 and US-12 occurred at night when speeds were likely faster, reduced light level might further prohibit drivers' response abilities resulting in more frequent collisions at night.

Surrounding habitat is likely an important factor in temporal factors associated with EVCs. Lao et al. (2011) found that collisions were more likely to occur in rural areas. This might explain why there were, on average, more collisions along US-12 than I-90, for the past five years since the underpass is located in a relatively rural area with few urban settings and low human population numbers. Lao et al. (2011) attributed this to animal populations likely being different in urban and rural settings. Additionally there is only one underpass in my study area along US-12, as opposed to several along I-90. The lack of safe crossing opportunities along US-12 could also exacerbate the frequency of EVCs. Both study sites in Washington have large elk populations, but it is possible that more elk are hit in the Cowlitz River Valley due to its rural setting especially since roads are not lit, and visibility is greatly reduced at night in conjunction with a lack of safe crossing opportunities altogether.

Regardless of an urban or rural setting, surrounding vegetation and overall habitat type adjacent to roads has been shown to result in more AVCs (Forman et al. 2003, Keller and Largiader 2003, Kramer-Schadt et al. 2004, Litvaitis and Tash 2008). Many studies have found that ungulate collisions occur on roads surrounded by forest-open habitat (Finder et al. 1999, Malo et al. 2004, Gunson et al. 2009) while others document ungulate association with riparian areas (Bellis and Graves 1971, Feldhammer et al. 1986, Finder et al. 1999, Malo et al. 2004, Gunson et al. 2009). Overall, wildlife show attraction to roads near areas with adequate foraging opportunities, thus increasing their risk of collisions (Gunson et al. 2011). In this study, roads bisect landscapes that provide quality habitat, and elk are often seen grazing in or around underpasses. Therefore, areas where road curvature reduces visibility (Bashore et al. 1985) but provides quality grazing habitat could be especially dangerous, especially at night when motorists see less clearly. Ultimately, both I-90 and US-12 were built to follow the grade of least resistance, where animals also typically travel (Boone et al. 1996, Schippers et al. 1996, Larkin et al. 2004). This factor may influence the frequent occurrence of EVCs in these study areas.

Overall, many factors exist that might contribute to elk collisions during different light levels, especially driver reactions and surrounding habitat. Traffic volume, another likely influential factor, will be explained further below.

Light Level and Traffic Volume

Collisions with elk can be especially detrimental because of their large size and mobility, often resulting in property damage to vehicles, injury or death. Though no data exist on the amount of successful crossing attempts of elk at grade in Washington State, collisions may be used as an indicator if we assume that the number of collisions is proportional to safe crossings made at grade. Previous studies have shown that traffic volumes may indicate when an elk will cross at grade (Gagnon et al. 2007a, Gagnon et al. 2007b). Therefore, using all EVCs that occurred within the study area sites of the motion-triggered cameras from years 2009-2013, I found that traffic volumes associated with EVCs significantly differed between light categories except between dusk and dawn, and night and dawn. Furthermore, both light level and site demonstrated a non-linear relationship to the log-transformed values of traffic volumes during times when elk were struck by vehicles. Overall, I-90 had significantly higher traffic volumes than US-12, and traffic volumes were highest during the day (Table 5).

Previous studies also observed a high frequency of collisions at night when traffic was typically lower. Millspaugh (1999) found that elk move closer to roads at night when traffic volume is lower (Millspaugh 1999). Dodd et al. (2007) found that elk crossed at grade during lower volumes of traffic and moved away during periods of high traffic. Therefore, similar to these studies, the high frequency of collisions at night might indicate that some elk avoid roads during periods of high traffic volume during the day, and move closer to roads when there are fewer disturbances from traffic, which is at night.

Other studies have showed the opposite effect, with negative effects of roads increasing with higher amounts of road traffic (Gagnon et al. 2007b), or more WVCs occurring during periods of high traffic (Gunson et al. 2003). Elk, though highly mobile, may not be able to judge length and speed of oncoming vehicles making a collision with a crossing elk more likely when more vehicles are on the road.

Interestingly, some studies have shown that despite high traffic volumes, elk will use habitat closer to roads if a visual barrier exists (Montgomery et al. 2013) or if suitable grazing habitat is nearby. This could contribute to explaining the differences in EVCs found along I-90 and US-12 in the study areas. In North Bend, along I-90 elk are found close to the road, but rarely cross it. According to Montgomery et al. (2013), the dense vegetation obscuring the road may cause elk to feel more protected from humans, anthropogenic disturbances like noise, or hunting pressures. Along US-12 in the Cowlitz River Valley, elk may use the underpass for access to the riparian area adjacent to the Cowlitz River but cross the highway otherwise since there is little vegetation along the roadside to prohibit movement.

Despite higher levels of traffic along I-90, fewer collisions occur annually in this study area per year in comparison to the US-12 study area. Similar to Lao et al. (2011) who found that number of lanes has a negative effect on animal presence, the larger number of lanes along I-90 might create more of barrier effect for elk. This agrees with the barrier effects observed by Dodd et al. (2007) and Jaeger et al. (2005).

Other studies have showed that elk as well as other species might shift their temporal behaviors because of anthropogenic disturbances (Neumann et al. 2013, Northrup et al. 2012). Since collisions with elk in my two study areas occurred more frequently at night during lower traffic volumes, it is possible that these normally crepuscular species are temporally adjusting their behavior in response to traffic, or another disturbance attributed to the road.

Overall, Gunson et al. (2011) noted that temporal analyses of traffic volume effects are complicated. Some studies did not reveal a temporal pattern between traffic and AVCs (Shepard et al. 2008), others reported mixed results (Bissonette and Kassar 2008), and others were confounded due to the barrier effect (Jaarsma et al. 2006). Analyses of traffic volumes are difficult to compare especially since road types differ dramatically, as do wildlife responses to them. Ultimately, more crossing data needs to be collected to define a pattern of use for elk in response to traffic volume, though a relationship seems to exist. As of now, too many entangled factors appear to contribute to elk crossings to make succinct conclusions.

Seasonality

Due to high elk activity levels during the rut when elk try to find suitable mates and resources, I expected to see more collisions occur during the fall. EVCs were observed to be different along I-90 and US-12 study sites according to season, with most overall collisions occurring during the spring and fall (Table 7, Figure 13). However, collisions differed substantially by season along I-90 and US-12. Along I-90 most collisions occurred during the spring and fall, whereas most collisions along US-12 occurred during the winter and summer, similar to other studies that did not show seasonal differences in elk activities (Wichrowski et al.

2005). Regardless, small sample sizes made resulting seasonal analyses difficult, but several factors may explain the high frequency of EVCs during different months. Besides the factors that influence seasonal underpass use such as foraging to meet energy requirements, anthropogenic influences, migration and gender, other factors like age might play a role.

As other studies have revealed the importance of animal habituation to roads and crossing structures (Barrueto et al. 2014), younger, or migratory elk unfamiliar with underpasses may attempt to cross at grade and are more likely to be struck by a vehicle. Though there is no data on gender or age reported by Washington State Patrol, future work may want to consider age and gender in predicting EVCs.

Telemetry

Other studies have shown that elk move towards highways during levels of lower traffic, similar to my findings using elk fitted with GPS collars in North Bend (Gagnon et al. 2007b). GPS telemetry points clearly show that three collared elk used for this study in the North Bend vicinity appear to rarely cross I-90, though they often come close (Table 8). According to Starr (2012), few elk had home ranges on both sides of the highway despite suitable habitat. The observed distances of elk in relation to I-90 were not the same as expected values based on light level. This suggests that I-90 poses a serious barrier to movement not only during certain times of the day, but altogether, which is similar to findings from other studies (Mueller and Berthound 1997). Like Gagnon et al.

(2007a), who found that elk moved farther from roads during periods of high traffic, elk in North Bend demonstrated a similar pattern. When traffic volumes were log-transformed, a strong non-linear relationship between traffic volume and distance to the road was observed, suggesting that elk are found further from the road during peak traffic volumes.

Adjacent foraging opportunities and habituation likely influence how close elk are found to I-90 in North Bend. Ample riparian habitat along the highway in North Bend may influence elk to rank their nutritional requirements higher than disturbance brought by roads. However, since these elk are often found within the city limits, they might also be habituated to the noise from the highway, similar to other observed elk (Barrueto et al. 2014). Overall, elk demonstrated a non-linear relationship to traffic volume suggesting that elk moved farther from the road as traffic volume increased. More data needs to be collected to tease apart influential factors like vegetation and habituation so that a clearer pattern may emerge.

Conclusion

In conclusion, this study's efforts and findings highlight the importance of collaborative science, research and adaptive management between government agencies, academia and non-governmental entities. By working within a strong collaboration nexus, I was able to evaluate the ability of existing underpasses' abilities to provide safe passage for elk below grade. Ultimately I discovered that elk most frequently used underpass structures and were struck by vehicles most often at night when traffic volumes are usually lower. Because most elk activity near the underpasses and roads in the study area occurs outside of crepuscular time periods when elk have been reported to be most active, the findings of this research suggest that elk are shifting their normal behavior patterns. Additionally, elk most frequently used underpasses during the summer and fall, likely in conjunction with forage needs and life cycle habits. Elk collisions did not show a clear pattern between seasons; however a small sample size may be to blame. Collared elk in the Upper Snoqualmie River Valley were observed to stay close to I-90, but rarely crossed it, suggesting an affinity with riparian areas adjacent to the highway, and habituation to the road. Overall, underpass structures were shown to effectively allow elk passage safely below grade. Despite the fact that the three bridges in these study areas were not built intentionally for wildlife, the structures contribute to promoting safe movement opportunities for elk. With some retrofitting including making passages longer, wider and taller and fencing in these areas, as well as vegetation management, these structures have the potential to mitigate for even more of the WVCs that occur in these areas. Additional underpasses and overpasses designed specifically for wildlife in areas with high rates of WVCs would be especially useful for habitat connectivity measures and safety.

Overall, I found that elk use of underpasses and collisions with vehicles differed according to light level, season, and traffic volume. While many explanations exist for these patterns, and each should be addressed and further studied, this is an important initial step in synthesizing many forms of data toward understanding elk-road interactions in Washington State. With a baseline understanding of when elk will use structures, further research into specific ways to decrease elk-vehicle interactions can be more effectively addressed.

Road ecology is still very much a new field of study, and basic questions including when elk will use underpasses and when they are likely to be hit by vehicles are important to study and understand. With this information we can further build upon and gain better insight into different factors influencing elk movement in relation to transportation infrastructure, keeping in mind that habitat connectivity measures are not a one-size-fits-all solution. Each species, population, and even individual responds to external anthropogenic influences differently. Roads however will likely only continue to increase in their extent across global landscapes. As these roads intersect wildlife populations and habitats, understanding the effects and being able to mitigate for them is vital to reducing WVCs, keeping both animals and humans safe on the road.

Chapter 3: Conclusions and Management Implications

Conclusions

As transportation networks continue to expand, conflicts between wildlife populations and humans will necessitate greater recognition and further study of these conflicts. More people and agencies are becoming aware of the negative effects that roads have on habitat connectivity and wildlife populations through direct mortality, resulting in increasing efforts to study and mitigate for some of these issues. Moving forward, transportation agencies must be especially proactive in addressing the intersection between modes of human transport and wildlife movement. Though this is no easy task, gaining an understanding of how different factors affect wildlife movement in relation to roads is critical to addressing current concerns and preventing future ones.

A fine-scale understanding of elk underpass use at three structures in Washington had never before been synthesized. Using a multidisciplinary approach to gathering data, this study used records from the WSDOT Carcass Removal Database, WSDOT Traffic Information, Washington State Patrol Collision Database, and GPS collar locations from the Upper Snoqualmie Valley Elk Management Group to understand when elk most frequently move through underpasses or when they are struck by vehicles according to light level, season and traffic volume. Though the literature has documented regular activity of elk (*Cervus elaphus*), less is known about their activity levels at these underpasses. It is important to understand whether or not elk incorporate underpass use directly into their movement, and whether other factors are still prohibiting elk from using them.

I discovered that three underpasses in Washington provided adequate safe crossing opportunities for elk. However, a majority of these crossings occurred during the nighttime, when elk are generally not thought to be most active. This suggests that some other, possibly anthropogenic influence, may be influencing elk behavioral patterns with relation to underpass use. Many of these crossings occurred during summer and fall, in association with the growing season and rut, when elk would normally be active. This suggests that forage quality and typical life cycle behaviors may influence crossing rates accordingly. Most crossings also occurred at night, when traffic volumes were typically lower. This suggests that traffic volume may influence crossing rates of elk. Overall the factors studied here suggest that light level, season and traffic volume are influential factors in elk use of underpasses and collisions. This was an initial synthesis of several data sets, but more research over a longer period of time would provide a better understanding of elk movement in relation to transportation infrastructure. However, the underpasses in these locations do in fact show their ability to facilitate safe wildlife movement under busy highways. This is important in mitigating for barriers to wildlife movement and connecting habitats, though more research is necessary to gain a better understanding of the temporal and seasonal effects that roads and traffic volumes may have on elk use of underpasses.

Management Implications

Many management implications associated with elk research have been suggested to date. Previous studies have focused on the influences of traffic volume, vegetation, road size, adjacent habitat, surrounding vegetation, gender, age, or seasonal and temporal variations (Dodd and Gagnon 2011, Webb et al. 2011, Barrueto et al. 2014, Clevenger and Waltho 2003). Each of these may be an important factor in addressing the effects of roads and the ability of safe crossing structures to provide permeability and passage for wildlife. As scientists learn more, it paves the way for more research and a finer understanding of elk responses to anthropogenic disturbances and how humans can use infrastructure to help alleviate some of these pressures.

Indeed, many other researchers have also brought attention to areas in need of research. More specific parameters should also be evaluated including: 1) Most effective location of structures, 2) Proper dimensions for species of interest, 3) Approaches in terms of migration effectiveness, 4) Surrounding vegetation, 5) Amount of residual cover, 6) Fencing funneling animals towards structures, and 7) Conditions including noise levels all need to be monitored to better understand wildlife use of crossings (Glista et al. 2008). If road mitigation measures including underpasses are not adequately evaluated, results could lead to mismanaged wildlife populations and wasted physical and fiscal resources (Grift et al. 2013). Indeed, the ability of corridors to effectively connect landscapes has long been questioned. Reviews of the literature acknowledge the difficulty in quantifying this because each corridor is likely unique with respect to: 1) Target species, 2) Surrounding landscape, and 3) Infrastructure and study design (Beier and Noss 1998). Since the field of road ecology is relatively young, there are many aspects of road ecology where more research is warranted.

Recommendations for Future Research

1.) Continue and increase monitoring efforts of existing bridges and culverts
    a. Increase the number of monitored structures
    b. Continue collecting data so that yearly differences may be accounted for
    c. Identify additional high priority areas using carcass removal information and WVC information

This study was the first attempt to use data gathered from motion-triggered cameras, carcass removal reports, collision reports and GPS collars to understand temporal factors of elk movement at or below grade. Therefore, I used structures that had been part of existing monitoring efforts. With a better understanding of elk movement and affinity for structure types, a greater sample size using more structures would improve future analyses. Possibly using carcass and collision information to identify high priority areas could be used (Teixera et al. 2013). Furthermore, collecting data for multiple years at structures would help reveal trends over time and increase the number of replicates, making analyses with ANOVA possible. Clevenger and Waltho (2003) state that lack of information about the effectiveness of wildlife crossings is partly due to lack of experimental design, resulting in mostly observational data.

Now that WSDOT has synthesized preliminary data, hopefully the agency can move more towards an experimental design and develop studies to ask and answer more specific questions. Monitoring structures in these areas that could be used to facilitate wildlife movement would be warranted, helping WSDOT scientists understand wildlife movement in relation to roads and implement mitigation measures. Measuring success of at grade crossings is problematic, and rarely accomplished. However without this metric, a comparison to safe crossings below grade is difficult. In the future, WSDOT may consider deploying cameras over stretches of roads at grade so that a comparison can be made between crossings at grade and below grade. This would enable the department to ascertain the actual success rate of underpasses for providing safe crossing alternatives for wildlife.

2.) Improve/reconcile differences in reporting methods between collision records and carcass removal records

In Washington State, WSDOT records indicate an average of 139 elk carcasses removed from state-maintained roads each year according to the past 5 years' worth of data. For that same time period, Washington State Patrol records indicate an average of 108 collisions between elk and vehicles (Figure 11). These records represent a minimum count of elk that are injured/killed on state maintained roads each year. It is important to note that these are absolute minimum numbers and that the negative effects of roads on elk are likely much larger. Though carcass removals and collision data are some of the only available data for use in quantifying direct effects of roads on elk, studies have shown the two datasets differ significantly (Huijser et al. 2008). In fact, according to a project completed for WSDOT using both carcass removal and collision data, Wang et al. (2010) found that only 27 percent to 37 percent of Collision Report data matched Carcass Removal data. Researchers found that a combination of the two datasets increased total records by 13 percent to 22 percent (Wang et al. 2010) indicating that either dataset alone may be insufficient. Ultimately a well-rounded understanding of the conflicts between roads and wildlife requires various datasets, and a multi-perspective view to analyze properly. Therefore, despite limitations in both datasets, both contribute to researchers' understanding of elk-vehicle collisions and should be used.

3.) Improve terminology and methodology between similar studies

Though some of the results in this study are similar to previous studies found in the literature, it was often difficult to make comparisons between studies. According to Gunson et al. (2011) when completing a review of 24 published manuscripts, comparisons were difficult even between studies focusing on the same species. Most studies, especially temporal studies, use different categorizations of time or define light levels differently. This study attempted to use light based on stringent calculations of sunrise, sunset and twilight periods based on the Sun's position to Earth and corresponding amount of visible light. Therefore, the dissimilarities between this study and other studies may be explained by a lack of comparable factors.

4.) Conduct a DNA Hair Snag Analysis

Cameras do not allow us to identify individual animals unless they have some unique feature. A DNA hair snag analysis would inform us about the number of individuals that use crossing structures, their gender, and if they continue to use structures over a long period of time.

5.) Include gender information in collision reports

There may be a gender bias in animals that are struck by vehicles. Previous studies have shown that male sub-adults are killed on roads most frequently (Gunson et al. 2003). This might indicate that animals traveling longer distances are more likely to get hit on roads, especially during the rut when male elk travel long distances to find mates, thus accounting for seasonal increases in EVCs. It is also possible that elevated hormonal levels of males in the fall during the rut might make males less aware of their surroundings and more likely to be hit be a vehicle.

6.) Continue monitoring elk with GPS collars

   a. Additional collaring of elk
   b. Standardize collar schedule
   c. Collar females and males
   d. Collar elk in more geographically diverse locations

Locations of elk in relation to I-90 were gathered from a partnership with the USVEMG. Though more than 10 cow elk have been collared over the past few years, only three were used in this study because they were collared for at least one during the same time. All other collars were deployed at different dates, even years and the collar schedules were not succinct, some missing fixes for days. Increasing the number of collared elk would increase the sample size and possibly help make a more conclusive analysis. Collaring bulls in addition to cows would help us understand differences in gender, and movement patterns throughout the year. Finally, collaring elk in geographically diverse locations would help the DOT understand how different types of roads may affect different populations of elk. Since several hot spots exist around the state where elk are frequently hit on highways, understanding how elk move at one location alone is inadequate. Elk need to be collared in multiple problem areas so that the most effective mitigation techniques may be applied.

7.) Implement studies addressing effects of road and human noise on elk behavior

Highways and vehicles are sources of anthropogenic disturbances, especially noise. If noise acts as a repellent during underpass use, attempts to reduce noise are important (Gagnon et al. 2007b). If noise from highways causes animals to flee and instead cross over highways, then additional fencing acting as a funnel into such crossings may be necessary (Gagnon et al. 2007b) or attempts to reduce noise may be important. Though elk in the Upper Snoqualmie Valley may already be habituated to noise, those in the Cowlitz River Valley may be greatly influenced by vehicles and associated noise. WSDOT might consider studying flight behavior and effects of noise from video and camera images in addition to devices deployed around the same underpasses to record types and intensities of noise.

8.) Manage riparian areas

    a. Increase vegetation at some underpasses to entice elk to use underpasses or dissuade them from crossing the road

Effective vegetation management could be used to attract elk to underpasses or dissuade their ability to cross roads. Both study areas have underpasses surrounded by riparian areas due to the proximity of the South Fork Snoqualmie River and the Cowlitz River. Elk are naturally attracted to riparian areas due to the ample forage they provide. Therefore, because elk may move closer to roads that are surrounded by high quality habitat, future wildlife crossings should be located in such areas to increase habitat effectiveness (Gagnon et al. 2007b). Furthermore, vegetation can also be used in areas without safe crossing opportunities. In areas where roads intersect critical habitat, barriers like dense vegetation may disguise the visual and auditory disturbances caused by roads (Montgomery et al. 2013). Such screening vegetation could be used to help researchers better understand elk habitat selection near roads (Montgomery et al. 2012).

9.) Limit human access to some underpasses

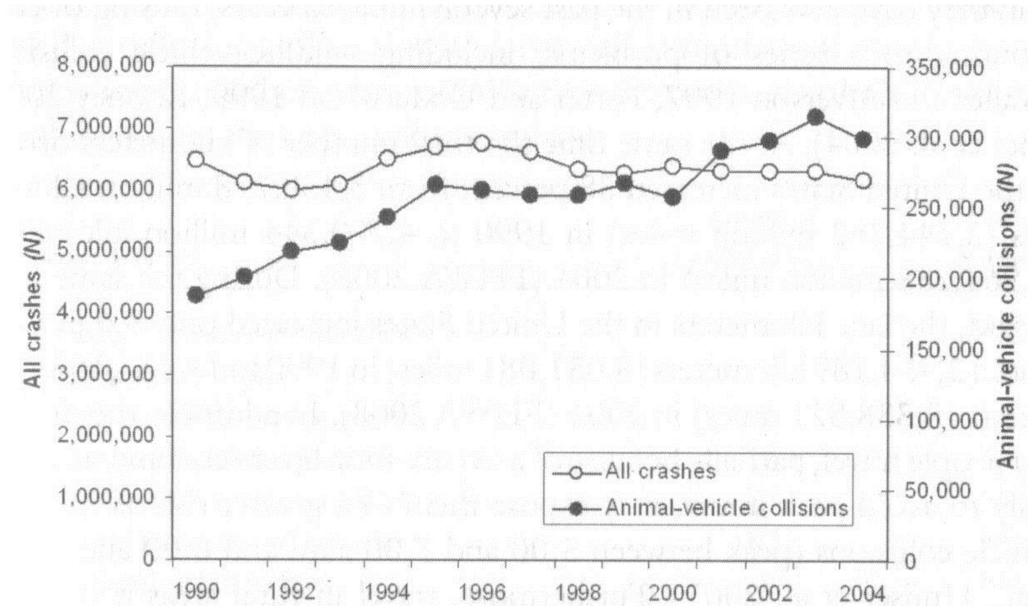
Human presence at underpasses may discourage elk use. Therefore, continuing to document and gain more evidence of this negative relationship is necessary. Limiting human access to underpasses, especially during times of peak elk activity, is also important. If elk are shifting their normal behavior patterns in an effort to avoid humans, this could have long-term consequences on their survival and health (Webb et al 2011). Limiting human exposure may help decrease that negative effect.

10.) Continue with an interdisciplinary approach to understanding effects of roads and how existing or future underpass design can mitigate for effects

The increasing needs of humans often conflict with efforts to protect the environment, and we are now tasked with trying to balance these needs. Roads have been an increasing part of the landscape for 100s of years now, but only recently have humans become aware of the immense impacts these roads have had on wildlife. The nascent field of road ecology has only begun to address these issues. Understanding issues in road ecology requires much knowledge including expertise in roads and transportation infrastructure, wildlife ecology and biology, engineering, design, hydrology, and chemistry. Since the issues contributing to habitat fragmentation are so complex, their solutions must be equally innovative. This often requires an interdisciplinary approach to be successful.

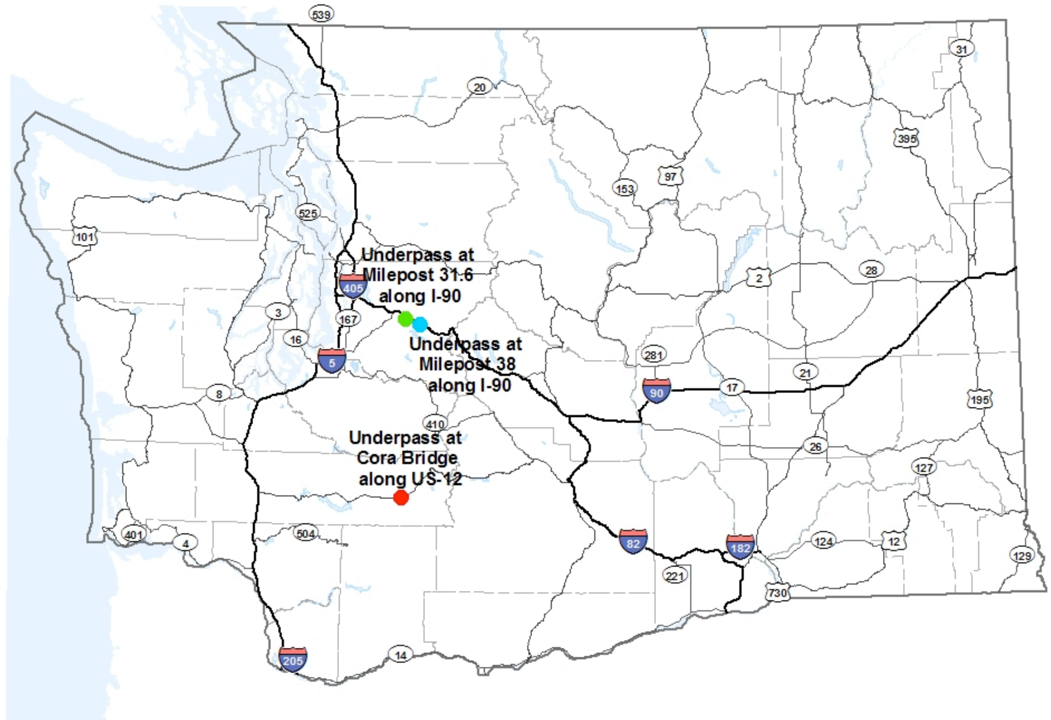
In Washington State, problems with WVCs are addressed using dynamic efforts between state agencies, non-governmental groups and academia. The interdisciplinary approach taken in this thesis research involved the sharing and analysis of multiple data sets to understand the temporal and seasonal movement patterns of elk in relation to transportation infrastructure above and below grade. With additional research and management efforts, we can continue collecting better data to analyze this issue more succinctly and create a safer highway system for drivers, while protecting wildlife populations and increasing habitat connectivity.

Figure 1: Total Collisions versus Wildlife-Vehicle Collisions



NOTE- Total vehicle collisions have remained ~ 6-7,000,000 from 1990-2004 while wildlife-vehicle collisions have increased from ~ 200,000-300,000 (Huijser et al. 2008).

Figure 2: Study Areas in the Upper Snoqualmie Valley and Cowlitz River Valley



NOTE- Motion-triggered cameras were deployed around three underpasses, and corresponding stretches of highway were analyzed.

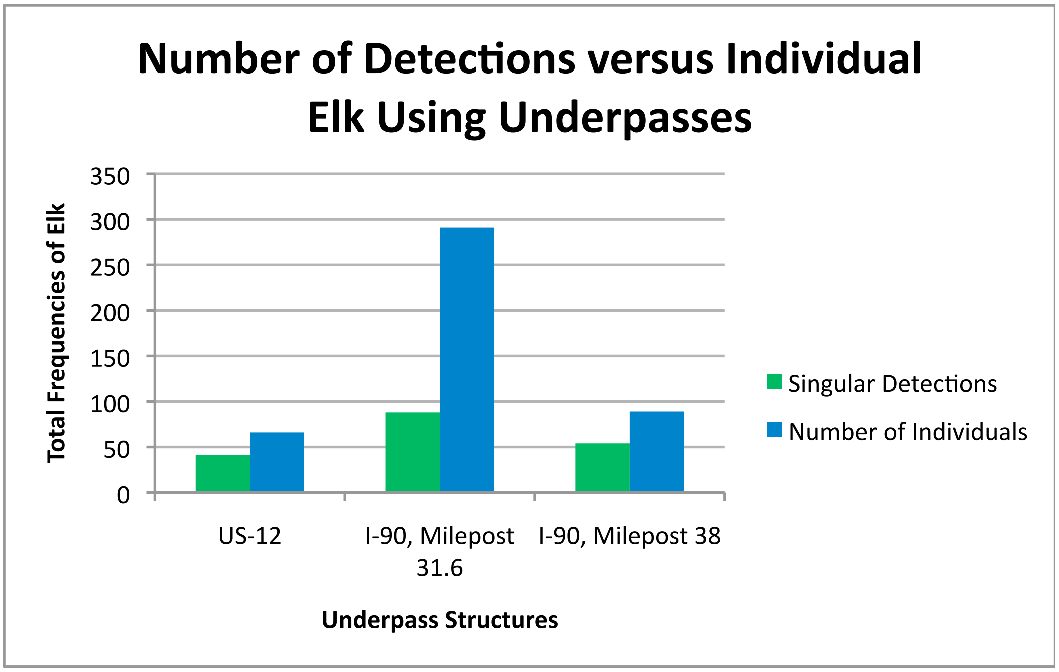
Figure 3: Study Area in the Upper Snoqualmie Valley

NOTE- Eight motion-triggered cameras were deployed around these two underpasses, and a portion of I-90 was analyzed.

Figure 4: Study Area in the Cowlitz River Valley

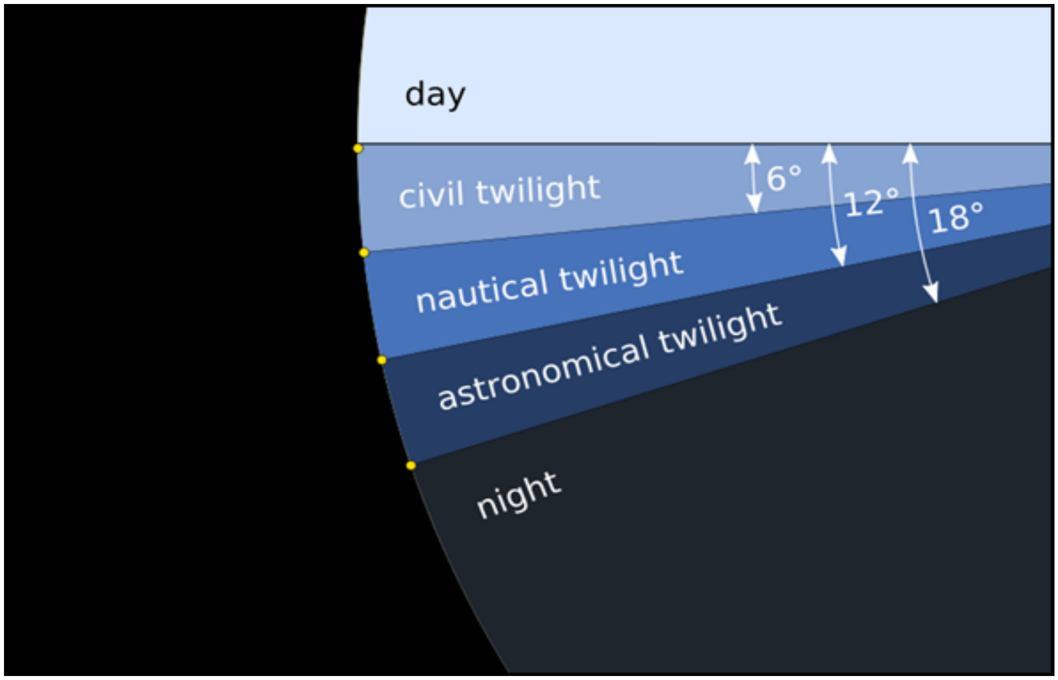
NOTE- Three motion-triggered cameras were deployed around one underpass, and a portion of US-12 was analyzed.

Figure 5: Number of Detections versus Individual Elk Using Underpasses



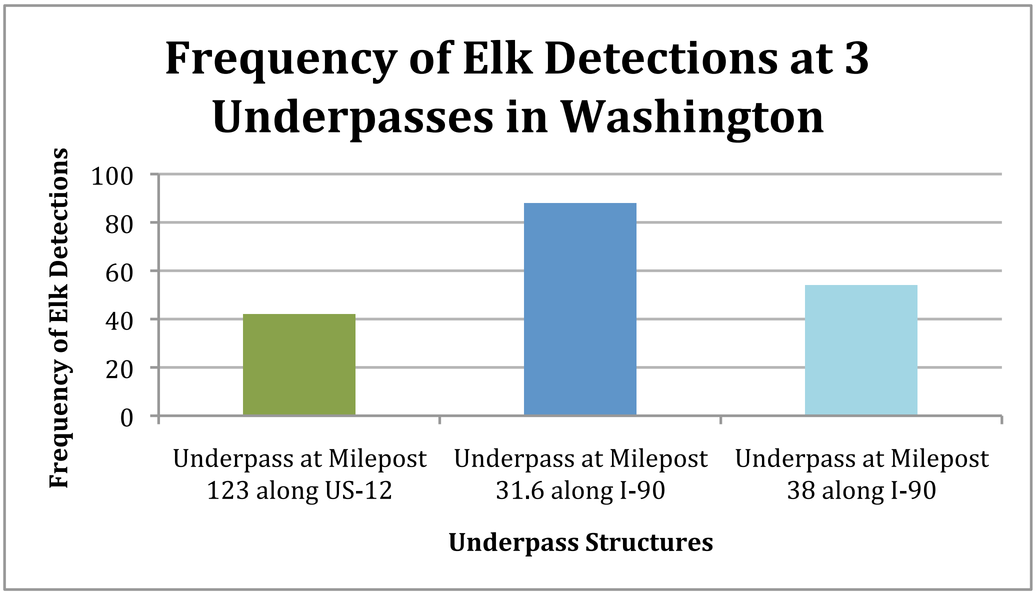
NOTE- This graph represents the difference between numbers of total individuals of elk who crossed through underpasses and singular detections that did not take multiple individuals into account.

Figure 6: Categories of Twilight



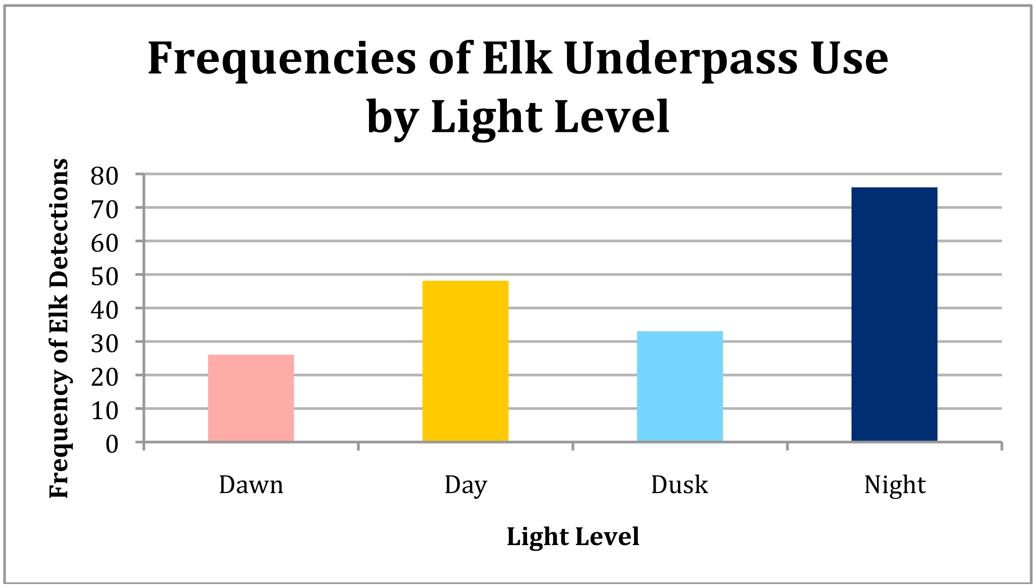
NOTE- This graph represents the designation of twilight according to the angle of the sun on Earth's horizon (Reid 2014).

Figure 7: Frequency of Elk Detections using Three Different Underpasses



NOTE- Total detections for the underpass along US-12 were collected from 2012-2013. Total detections for underpasses along I-90 were collected during 2013.

Figure 8: Total Frequencies of Detections of Elk Movement through Underpasses



NOTE- Data was collected during 2012 and 2013 and combined according to light level for all three underpasses.

Table 1: Goodness-of-fit test Using Light Level and Site

Light	Site	Observed frequency	Expected frequency
Dawn	CB	6	5.8251366
Day	CB	4	10.754098
Dusk	CB	4	7.3934426
Night	CB	27	17.027322
Dawn	NB31.6	12	12.502732
Day	NB31.6	23	23.081967
Dusk	NB31.6	22	15.868852
Night	NB31.6	31	36.546448
Dawn	NB38	8	7.6721311
Day	NB38	21	14.163934
Dusk	NB38	7	9.7377049
Night	NB38	18	22.42623

Note- Light level categories (dawn, day, dusk, and night) and site (underpasses in Cowlitz River Valley and Snoqualmie Valley) were used as categorical variables revealing the differences in observed values from expected values.

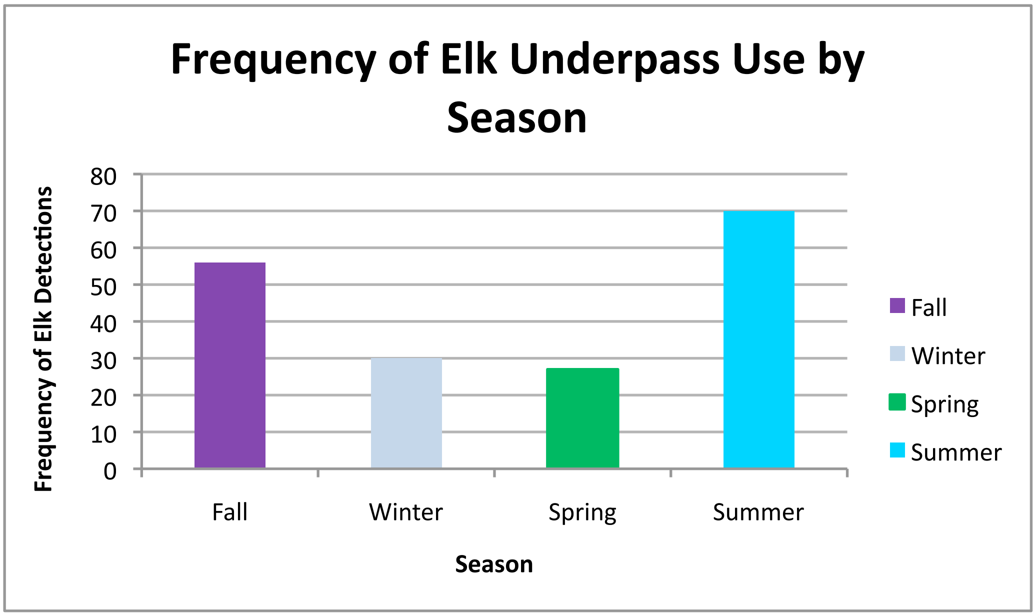
Table 2: Results of a 2-Way ANOVA using Light Level and Site

Source Variation	**df**	**Type III SS**	**Mean Square**	**F**	**p**
Main Effects					
Light	3	14.0331206	4.6777069	56.980373	.0000*
Site	2	35.7288122	17.864406	217.61101	.0000*
Interaction					
Light x Site	6	2.768169938	0.4613617	5.6199672	.0000*
Error	149	12.23190169	0.820933		

*Indicates a significant result at a = 0.5

NOTE-Light level categories (dawn, day, dusk and night) and site (underpasses in Cowlitz River Valley and Snoqualmie Valley) were used as independent variables and traffic volume was used as the dependent variable of elk detections by motion-triggered cameras at underpasses, 2012 and 2013.

Figure 9: Total Frequencies of Elk Movement through Underpasses by Season



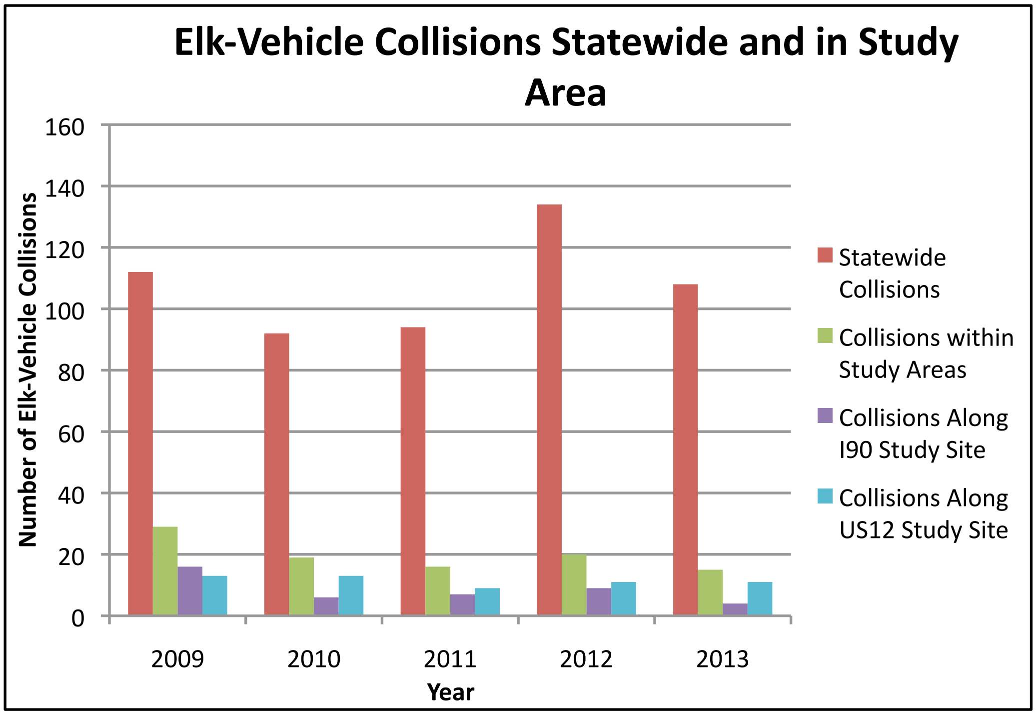
NOTE- Seasons are designated as fall, winter, spring and summer.

Table 3: Results of a Chi-square Goodness-of-fit Test using Season and Site

Season	Site	Observed frequency	Expected frequency
Fall	CB	13	12.54648
Spring	CB	1	6.0491803
Summer	CB	23	15.68306
Winter	CB	4	6.7213115
Fall	NB31.6	29	26.928962
Spring	NB31.6	19	12.983607
Summer	NB31.6	21	33.661202
Winter	NB31.6	19	14.42623
Fall	NB38	14	16.52459
Spring	NB38	7	7.9672131
Summer	NB38	26	20.655738
Winter	NB38	7	8.852459

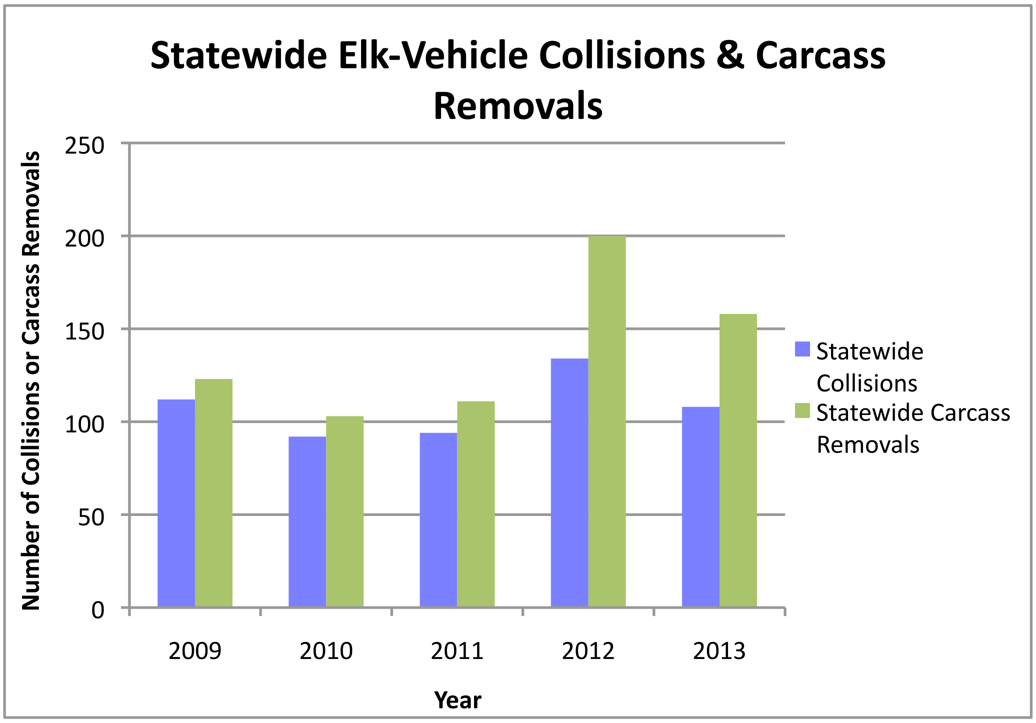
NOTE- Categorical variables of season (fall, winter, spring and summer) versus site (underpasses in the Cowlitz River Valley and Snoqualmie Valley) were used.

Figure 10: Total Elk-Vehicle Collisions in Study Areas



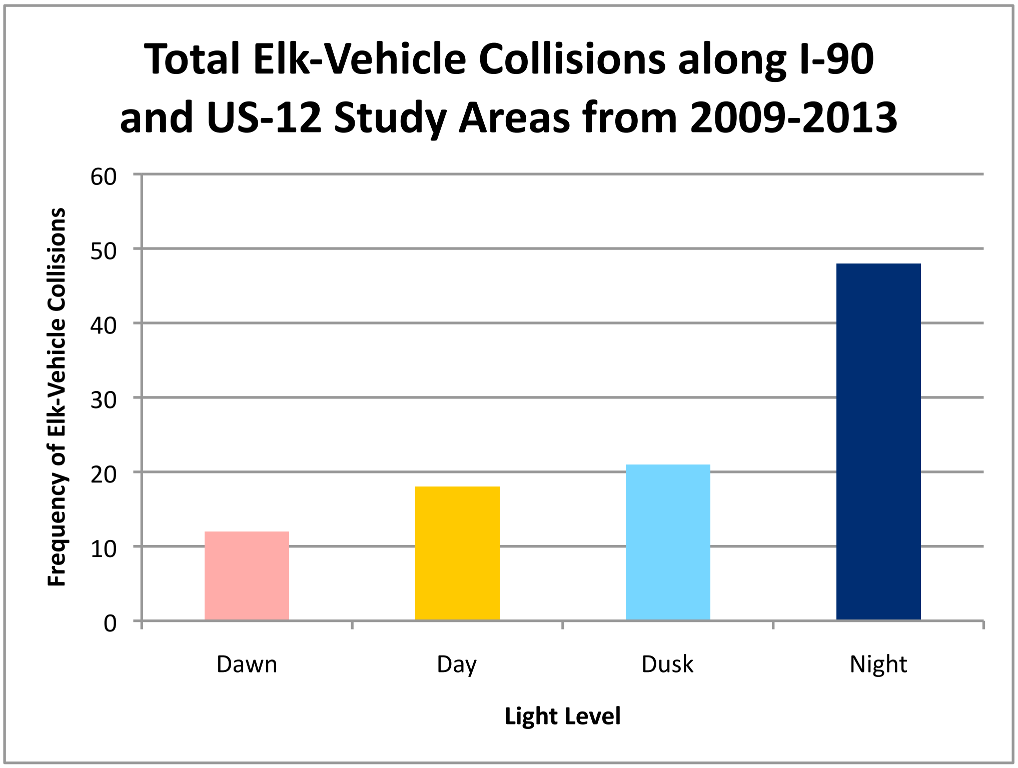
NOTE- Total collisions with elk along I-90 and US-12 within 32km of underpasses outfitted with motion-triggered cameras from 2009-2013.

Figure 11: Statewide Records of Elk-Vehicle Collisions and Carcass Removals



NOTE- Elk collisions and carcasses were recorded within 32km east or west of underpasses along I-90 and US-12.

Figure 12: Elk-Vehicle Collisions in Study Areas



NOTE- Collisions were used that were found within in 32km of underpasses according to light level.

Table 4: Results of a 2-Way ANOVA using Light Levels and Collisions

Source Variation	**df**	**Type III SS**	**Mean Square**	**F**	**p**
Main Effects					
Light	3	3.704417212	1.2348057	11.658879	.0000*
Site	1	43.02024955	43.02025	406.19175	.0000*
Interaction					
Light x Site	3	0.0259860934	0.0866203	0.817858	0.4874 not sig
Error	89	9.426095539	0.1059112		
Total	96	78.61487707			

*Indicates a significant result at a = 0.5

NOTE- Light level categories (dawn, day, dusk and night) and site (portions of I-90 and US-12 related to underpasses in Cowlitz River Valley and Snoqualmie Valley) were used as dependent variables versus the independent variable of log-transformed traffic volume when elk were struck by vehicles, 2009-2013.

Table 5: Student-Newman-Keuls Mean Separation Test of Collisions

Site Name	Mean (log traffic volume)	N (# samples)	Non-significant ranges
I-90	2.98641320017	41	a
US 12	1.33789764955	56	b

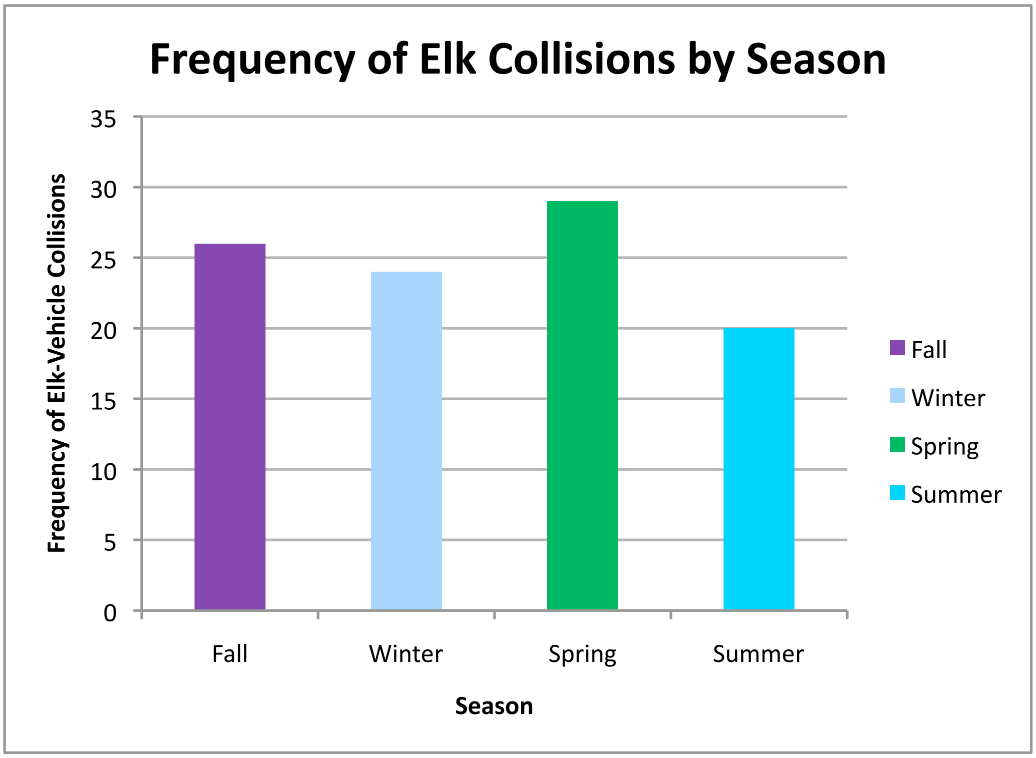
NOTE- Higher traffic volumes occurred along I-90.

Table 6: Student-Newman-Keuls Mean Separation Test of Traffic Volumes during Elk-Vehicle Collisions

Light level	**Mean (log traffic volume)**	**N (# samples)**	**Non-significant ranges**
Day	2.84632133548	18	a
Dusk	2.0714058502	21	b
Dawn	1.79525493841	12	C
Night	1.76280094409	46	C

NOTE- Traffic levels are highest during the day.

Figure 13: Frequency of Elk-Vehicle Collisions



NOTE- Collisions recorded within 32km of underpasses equipped with motion-triggered cameras along I-90 and US-12 by season were used.

Table 7: A Chi-square Goodness-of-fit Test using Season and Site

Site	Season	Observed frequency	Expected frequency
I-90	Fall	13	11.030303
I-90	Spring	18	12.30303
I-90	Summer	4	8.4848485
I-90	winter	7	10.181818
US 12	Fall	13	14.969697
US 12	Spring	11	16.69697
US 12	Summer	16	11.515152
US 12	winter	17	13.818182

NOTE- Seasons (fall, winter, spring and summer) versus site (underpasses in the Cowlitz River Valley and Snoqualmie River Valley) resulted in seasonal frequencies of collisions being different than expected.

Table 8: Elk Distances to the Highway

Animal	**Mean distance to road in meters**	**Standard deviation**	**Minimum**	**Maximum**	**N (number of fixes)**
339	1030.40	621.802644212	65.60	2366.82	633
341	1031.07	565.024682796	14.08	2410.58	1118
1550	1646.01	1084.19059117	49.07	5158.45	778

Table 9: A Chi-square Goodness-of-fit Test using Light Level and GPS Points

Animal	Light	Observed frequency	Expected frequency
339	Dawn	74	58.819692
339	Day	329	329.89087
339	Dusk	25	26.781732
339	Night	205	217.50771
341	Dawn	93	103.88691
341	Day	544	582.65085
341	Dusk	53	47.3017
341	Night	428	384.16054
1550	Dawn	68	72.293397
1550	Day	445	405.45828
1550	Dusk	29	32.916568
1550	Night	236	267.33175

NOTE- Elk distances to the road were different than expected according to light level.

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