Countermeasures for High-Risk Locations for Wildlife Related Crashes in Tennessee

Research Final Report from University of Memphis | Brian Waldron, Rebecca Butler, Travis DeVault, Gino D'Angelo, Janey Camp, Paulina Reyes | July 1, 2025 / Sponsored by Tennessee Department of Transportation, Strategic Planning, Research & Innovation Division. Research Office & Federal Highway Administration

THE UNIVERSITY OF MEMPHIS
Center for Applied Earth Science and Engineering Research

UNIVERSITY OF GEORGIA

DISCLAIMER

This research was funded through the State Planning and Research (SPR) Program by the Tennessee Department of Transportation and the Federal Highway Administration under ***RES#: 2024-03 Countermeasures for High-Risk Locations for Wildlife Related Crashes in Tennessee.***

This document is disseminated under the sponsorship of the Tennessee Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Tennessee and the United States Government assume no liability of its contents or use thereof.

The contents of this report reflect the views of the author(s) who are solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Tennessee Department of Transportation or the United States Department of Transportation.

4. Title and Subtitle *Countermeasures for High-Risk Locations for Wildlife Related Crashes in Tennessee*		5. Report Date July 2025 6. Performing Organization Code
7. Author(s) Brian Waldron, Rebecca Butler, Travis DeVault, Gino D'Angelo, Janey Camp, Paulina Reyes		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Memphis – CAESER 3675 Alumni Ave. Memphis, TN 38152		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 74736
12. Sponsoring Agency Name and Address Tennessee Department of Transportation 505 Deaderick Street, Suite 900 Nashville, TN 37243		13. Type of Report and Period Covered Final report – Aug. 1, 2023 to July 30, 2025. 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A study funded by the Tennessee Department of Transportation (TDOT) and the Federal Highway Administration under RES2024-003 was conducted to assess the occurrence of wildlife-vehicle crashes (WVCs) along TDOT maintained routes in Tennessee and to explore potential mitigation strategies. WVC hotspots were identified by analyzing wildlife incident data from 2019 to 2023, with route segmentation defined by intersections. Many incidents involved deer. An extensive literature review informed the analysis of WVC causality and mitigation methods. Key factors influencing WVCs included time of day, weather, seasonality, and traffic density, with deer-related behaviors driving most incident patterns. Environmental conditions and traffic density were not found to be significant predictors. Various mitigation strategies were considered, including signage, auditory cues, odor deterrents, wildlife rerouting, and fencing. Fencing was identified as an effective mitigation strategy, yet its effectiveness was limited due to frequent intersections on most high-WVC routes, which restricted the possibility of installing continuous fence segments. A targeted field review of the highest WVC segments revealed infrastructure features such as underpasses, culverts, and stream crossings that could support mitigation, but implementation was constrained by road layout and ingress/egress points. Ultimately, the study recommended deploying flashing warning signage during peak WVC periods, especially in November, to alert drivers and promote behavior changes—such as reducing speed and increasing vigilance—that may reduce collision risks.

17. Key Words **Wildlife vehicle crash, mitigation, safety**		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 107	22. Price

ACKNOWLEDGEMENTS

We would like to thank the State of Tennessee Department of Transportation (TDOT) for this incredible opportunity to analyze the occurrence of wildlife vehicle crashes in the State of TN along its maintained routes and to address potential mitigation strategies to minimize incidents along roadways having historically high records of drivers hitting animals. Specifically, within TDOT, we wish to thank Michelle Hunt for her guidance throughout the project period, Pamela Boyd-Walker for her assistant with project administration, and Sue Lasser for assisting with project finances. We would like to thank David Duncan, Nicholas Barnard, Caleb Jeavons, Steve Goodman, Liz Hillard, Brandon Chance, and Shawn Wurst.

Executive Summary

A study was initiated through funding from the Tennessee Department of Transportation (TDOT) and the Federal Highway Administration under RES2024-03 to assess the occurrence of wildlife vehicle crashes (WVCs) in the State of Tennessee along TDOT maintained routes and to consider mitigation measures to reduce such occurrences. Determination of high-frequency WVCs was determined through densifying TDOT route segments, defined by intersections, with recorded wildlife incidents between 2019-2023, the vast majority being encounters with deer.

Guiding the characterization of WVCs statewide and long high-frequency WVC routes was an extensive literature review that identified several factors related to causes of WVCs and mitigation practices. Regarding causality, WVCs were assessed on time of day (i.e., lighting), weather condition, time of year, environmental conditions, and road traffic density. Mitigation practices encompassed signage, auditory response, odor deterrents, wildlife rerouting, and fencing, with the latter serving as a foundation for other practices.

With deer being the vast majority of WVCs along TDOT maintained routes and the remainder as undefined, many of the causes to WVCs were related to deer behavior, such as rutting in November which had the highest elevated counts of WVCs to time of day were deer are more active during dawn and dusk. Of the causes, WVCs were not deemed dependent on environmental conditions (i.e., prime habitat of forest-field mix) and traffic density. When applying mitigation strategies, a small subset of TDOT routes were investigated which correspondingly had the highest count of WVCs. Routes were detailed on the presence of bridges/underpasses, stream crossings, culverts, and secondary road/driveway/service road intersections – these linked to potential fencing.

Mitigation strategies reveal that of the high WVC impacted routes nearly all, with the exception of one interstate, had too many intersections from driveways and entrance roads to provide enough effective (>3 km) lengths for fencing, thereby also limiting the incorporation of other mitigation approaches like utilizing underpasses and stream crossings. Ultimately, recommended to reduce WVCs was to use flashing signage along high-collision routes during November, in the least, to bring attention to drivers of possible wildlife activity and to modify their behavior (e.g., use lower speeds, be attentive) that may avert a collision.

Contents

List of Figures

List of Tables

1.0 Introduction

Wildlife-vehicle collisions (WVCs) present an increasing problem in North America (Huijser et al. 2009). In the U.S. alone, it is estimated that there are 1-2 million WVCs per year with annual costs up to $8.4 Billion (Conover et al. 1995; Huijser et al. 2008). Increases in the number of roadways and highway miles have led to a growing number of WVCs with rising socioeconomic consequences such as driver safety and health (Sullivan and Messmer 2003; Bissonette et al. 2008). Collisions with large mammal species can result in considerable property damage or even human fatalities (Wells 2005; Bissonette et al. 2008; Huijser et al. 2008). Although collisions with smaller-sized wildlife are a frequent occurrence, large mammal-vehicle collisions (e.g., bear, moose, etc.) pose a greater concern due to their ability to cause significant injury or property damage (Wells 2005; Litvaitis and Tash 2008; Ha and Shilling 2018). It is estimated that there is one human death for every 3,441 deer (Odocoileus spp.)-vehicle collisions (Conover et al. 1995). Although only 4-10% of WVCs cause motorist injury, nearly 100% of WVCs with large wildlife species (e.g., bear, moose, etc.) result in considerable property damage (Huijser et al 2008). Additionally, damages caused by WVCs economic impacts by increasing insurance premiums (Hurley et al. 2009).

Wildlife crossing structures across roadways are mechanisms which can be used to reduce WVCs and decrease the likelihood of property damage or serious human injury (USDA-FS 2021). Wildlife-vehicle mitigation structures allow wildlife to cross under or over roads, often including the use of fencing to guide animals, to reduce WVCs by providing safe passageways for crossing (USDA-FS 2021). Initial installation and maintenance of WVC mitigation structures can be expensive; however, the cost-benefit ratio for their implementation, 3.0 for underpass and underpasses and 30 for wildlife fencing, outweighs all disadvantages (Wilkins et al. 2019). Mitigation structures increase benefit-cost ratios by decreasing vehicle collisions and their associated economic impacts, improving human safety on roadways, and increasing habitat connectivity (Bissonette and Adair 2008; Huijser et al. 2016). For example, in one case, an 80% reduction in large mammal WVC was achieved on long roadway lengths by implementing mitigation measures (Huijser et al. 2016).

As another consideration, roadways pose a serious ecological risk to wildlife by fragmenting ecosystems, resulting in negative genetic consequences (Sullivan and Messmer 2003; Sawaya et al. 2014; Sawaya et al. 2019; Edwards et al. 2022) and the survivability of wildlife populations is threatened by WVCs (Trombulak and Frissell 2000; Huijser et al. 2008). Roadways are also a concern for threatened or endangered species, and roadways can have catastrophic impacts on population densities of critical species (Blackburn et al. 2021). Therefore, it is imperative that future transportation construction decisions be made to incorporate habitat fluidity as road networks increase to accommodate a growing population (Sawaya et al. 2019). Wildlife crossing structures can reduce habitat fragmentation by connecting environments which would have otherwise been disconnected by roadways (Foster 1995).

Due to the considerable costs of wildlife collision mitigation strategies (> $1 million in some cases), it is imperative that implementation of WVC mitigation techniques incorporate species preferences, or they are likely to fail (Litvaitis and Tash 2008; Wilkins et al. 2019; Brennan et al. 2022). Knowing landscape characteristics associated with road mortalities for a particular wildlife species of interest can be important for WVC mitigation (Conard and Gipson 2006). Wildlife species vary in abundances and movement patterns throughout landscapes and these factors are associated with different collision densities (Saint-Andrieux et al. 2020). Management of focal species should incorporate strategies which target locations where species' preferred habitats intersect roadways and where WVCs are spatially clustered (Beasley et al. 2013). Wildlife-vehicle collisions are non-randomly aggregated along roadways (Eslinger and Morgan 2017; Cserkész et al. 2013) and there is a vital need for incorporating environmental and biological factors associated with WVCs (Saint-Andrieux et al. 2020).

Many agencies do not have designated personnel with job responsibilities directed at reducing WVCs and lack sufficient data for the purpose of documenting animal collisions (Sullivan and Messmer 2003). Agencies which report WVCs are often inconsistent in data reporting, which is alarming because quality data are important for accurately assessing WVC mitigation implementation and hotspot alterations over time (Huijser et al. 2007). Additionally, most WVCs go unreported, which may stem from drivers' attempts to avoid future insurance cost increases and can distort model results (Wilkins et al. 2019). Underreporting can skew the relationship between environmental factors and WVCs, obscuring the relationships between the variables (Snow et al. 2015). Models have some ability to predict WVC hotspots using underreported data; however, these models have less predictive power when underreporting is greater than 70% or in addition to spatial bias (Snow et al. 2015). Wilkins et al. (2019) noted the effects from underreporting can create extreme biases in the estimation of WVCs.

Vehicle collisions associated with wildlife are a problem in Tennessee along with the need to protect critical species of ecological and economic concern (Braunstein et al. 2020; Chapagain and Poudyal 2020; Tennessee Department of Safety and Homeland Security 2020). Mitigation strategies for WVCs are included in Tennessee Department of Transportation's (TDOT's) 25-year Plan which also aims to incorporate methods of habitat restoration (Transportation 2015). Therefore, herein we provide an exhaustive existing literature review on causes of WVCs and mitigation strategies appropriate for Tennessee roads, habitats, and animal species. We conducted extensive spatial analyses on WVC occurrences and reasons for such occurrences, assessed interdependencies among variables, and conducted temporal analyses to ascertain wildlife behavioral patterns. A set of mitigation strategies to reduce WVCs were investigated, and recommendations were provided.

2.0 Data acquisition and clean-up

Crash reports obtained first from a TDOT database (n=31,700), but records seemed limited to incidents with deer. A second dataset was acquired from the American Association of State Highway and Transportation Officials (AASHTO)(n=38,065) which included the same reports of deer incidents as from the TDOT database but also included 5,625 "other animal" as well as 740 other incident types (n=56) not related to this effort (e.g., shrubbery, boulder, traffic sign post, and others). Keeping only types that included "deer" and "other animal", a total of 37,327 (2 additional points found using these key words) were created into a point dataset in a geographic information system (GIS) (i.e., ArcGIS Pro).

Deer population data was obtained from a Tennessee Wildlife Resources Agency (TWRA) dataset where single sightings were represented using either county name or by latitude/longitude. The sightings by county data set were too course and was not in a transformative spatial format (i.e., polygon) for performing spatial analyses along road segments within a county nor amenable to use in analysis with vehicle crash incident point data. Hence, the TWRA data that contained geographic coordinates (n=366,855) were transformed into a GIS point layer. From a preliminary heat map developed using this dataset, downtown Nashville was shown as having an unprecedented number of sightings (i.e., tens of thousands). Upon further inspection, three locations were found to have stacked points representing 45,421 sightings. The explanation for this is that sighting locations were not recorded at the location where the deer was seen but instead were recorded at government offices. Hence, these were removed resulting in 321,434 deer sightings.

Other spatial data pertinent to this project were obtained from TDOT (i.e., fencing, culverts, maintenance routes, etc.), U.S. Fish and Wildlife Service (USFWS) (i.e., wetlands), Multi-Resolution Land Characteristics (MRLC) Consortium (i.e., national land cover dataset, forest canopy), TWRA (i.e., land where hunting is allowed [n=210; 1.74 million acres]), and TN Department of Health, or TREC Project (i.e., recreation sites such as state parks, greenways, national forests, national parks, etc. [n=2,378; 1.91 million acres]).

3.0 Methods

Two spatial analyses were performed pertaining to the association of WVCs to roads and the density of forest cover near roadways. The roadways are those maintained by TDOT and include interstates, highways, and primary and secondary roads.

3.1 Spatial analysis of crash incidents proximal to roads

The density of WVC along *TDOT maintained routes* (name of the GIS file) was determined through spatial analysis. It was observed in the TDOT maintained routes that there existed small road segments within longer road spans between intersections. If this was not addressed, then the association of WVCs to road segment would result in lower densities; hence, this had to be addressed first. An angular distance was then calculated between each WVC point and route, resulting in the shortest distance. As the road FID (i.e., attribute primary key) is captured along with the distance, the count of WVCs was obtained and joined to the new route layer for additional analyses and visual assessment.

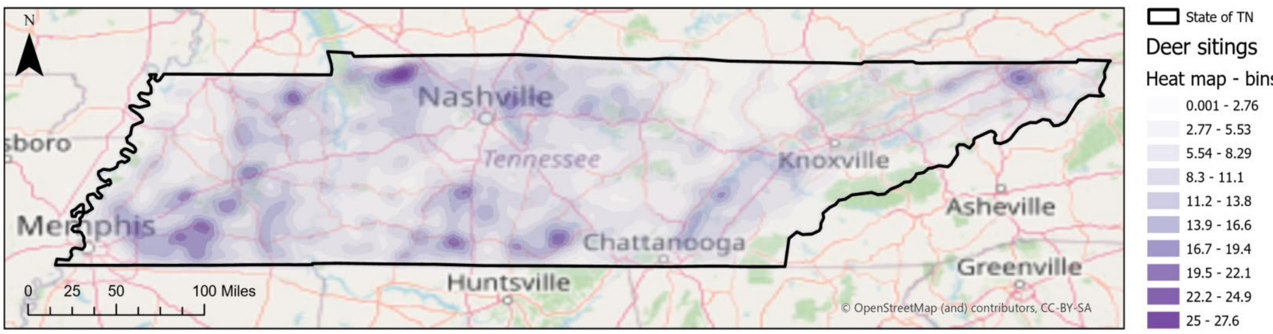
3.2 Remote sensing analysis of forest density proximal to roads

The MRLC produces a tree canopy raster for the United States where values range in percentages from 0-100% - a dense, full canopy coverage is represented as 100%. To determine the percent-threshold for the State of TN, a two-pronged approach was used: (1) perform a subjective comparison of the percent of forest against aerial imagery and (2) a quasi-quantitative assessment comparing percent of forest against known forested areas in Shelby County where the University of Memphis is located.

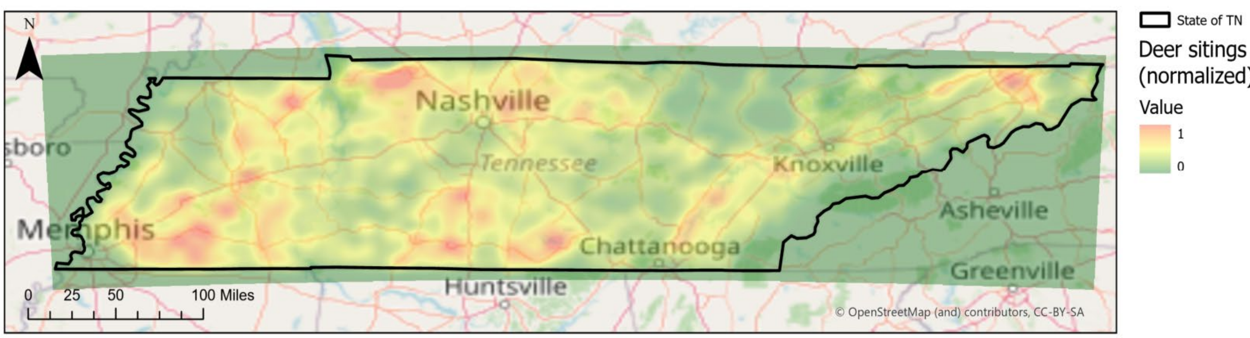
4.0 Results

4.1 Spatial analysis of deer population and crash incidents

To determine the correlation between deer population and crash incidents, heat maps of each dataset from TWRA and AASHTO, respectively, were developed. As the TWRA data only represented deer sightings, the AASHTO data was further processed to also only represent deer (n=31,700). The TWRA heat map using 321,434 sightings had a spatial bin range of 0.001 to 27.6 (Figure 4.1.A (a)) and the vehicle crash incident heat map had a spatial bin range of 0.001 to 8.40 (Figure 4.1.B (a)). To match high deer sightings with elevated vehicle crash incidents, both heat maps were normalized where 1.0 represented the high range value for each (see Figures 4.1.A (b) and 4.1.B (b)). Both normalized heat maps were then multiplied together resulting in a spatial bin range of 0 to 0.645 (Figure 4.1.C). To isolate areas where high deer population coincided with vehicle crashes, this new raster was conditionally sampled at multiplied normalized values of 0.0625, 0.125, and 0.25 with the maximum for each at 0.645, representing heat map ratios of 25:25%, 25:50%, and 50:50%. For example, using 50:50%, a deer sighting value at half the heat map maximum of 27.6 would be 13.8 or 0.5 normalized and a vehicle crash value at half its heat map maximum of 8.40 would be 4.20 or 0.5 normalized, such that multiplying the two normalized heat maps results in a value of 0.25. As shown in Figure 4.1.D (a-c), isolated hotspots grow outward from a minimum value of 0.25 (n=4 isolated areas) to 0.0625 (n=17).

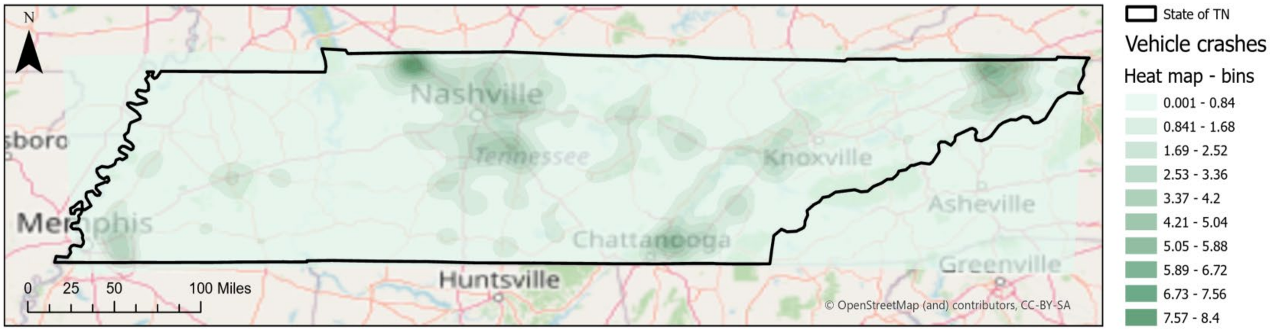


(a)

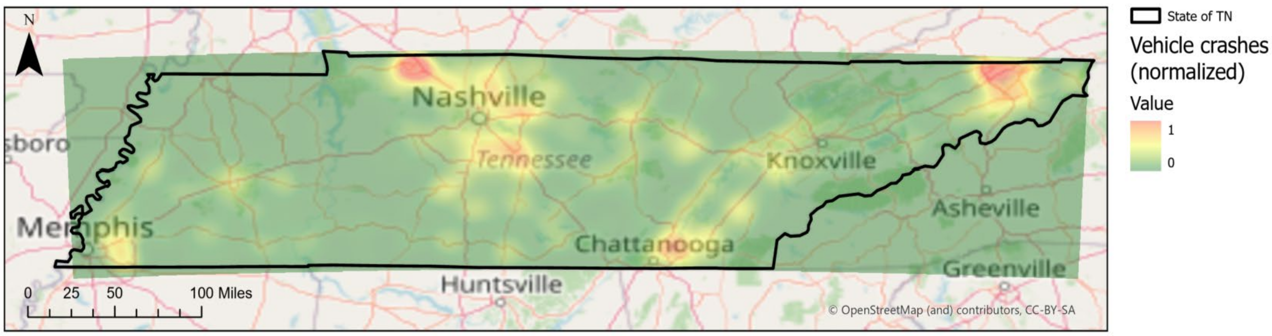


(b)

Figure 4.1.A. Deer sightings as (a) heat map and (b) heat map normalized.



(a)



(b)

Figure 4.1.B. Vehicle crashes as (a) heat map and (b) heat map normalized.

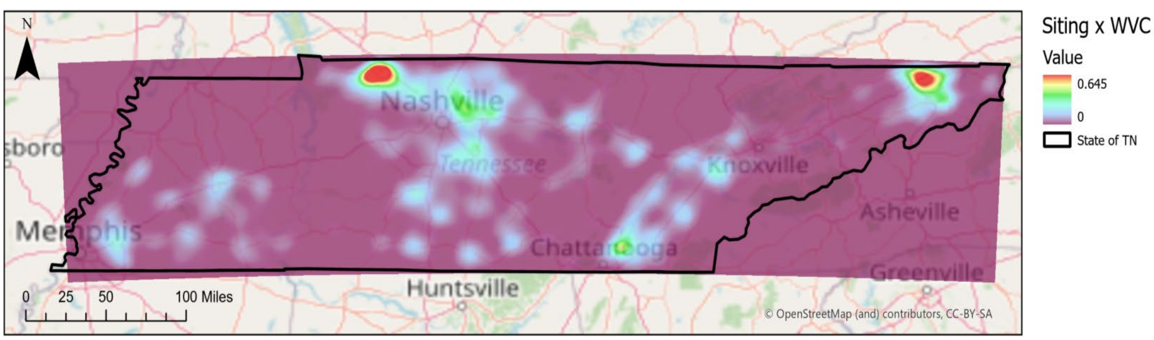
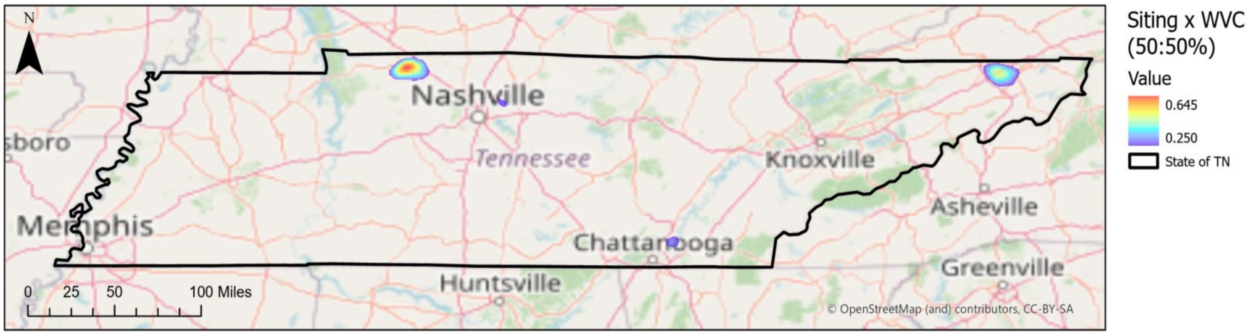
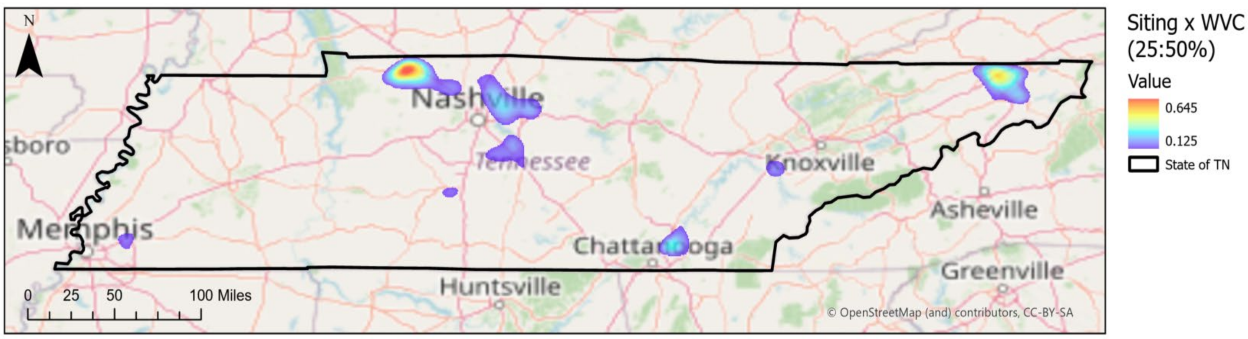


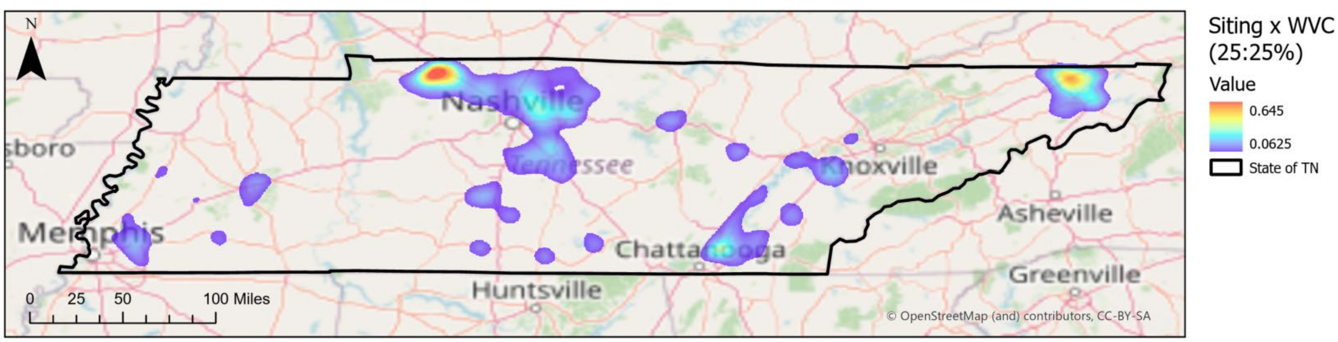
Figure 4.1.C. Raster resulting from deer sighting normalized raster being multiplied by the vehicle crash raster.



(a)



(b)



(c)

Figure 4.1.D. Conditional rasters of that in Figure 4.1.C. for heat map ratios of (a) 50:50%, (b) 25:50%, and (c) 25:25%.

4.2 Spatial analysis of crash incidents proximal to roads

As mentioned, it was observed in the TDOT maintained routes had some fragmentation between road intersections (see Figure 4.2.A). These small segments needed to be removed before associating WVC density to a route. There were 9,639 road segments in the original TDOT maintenance route GIS layer. To remove fractionation of a road into parts, the TDOT maintenance route layer was dissolved on **nlor_rt2** (i.e., route name), points were created at each road intersection, then the dissolve layer was split by the intersection points, resulting in 4,923 road segments – a reduction of 48.9%.

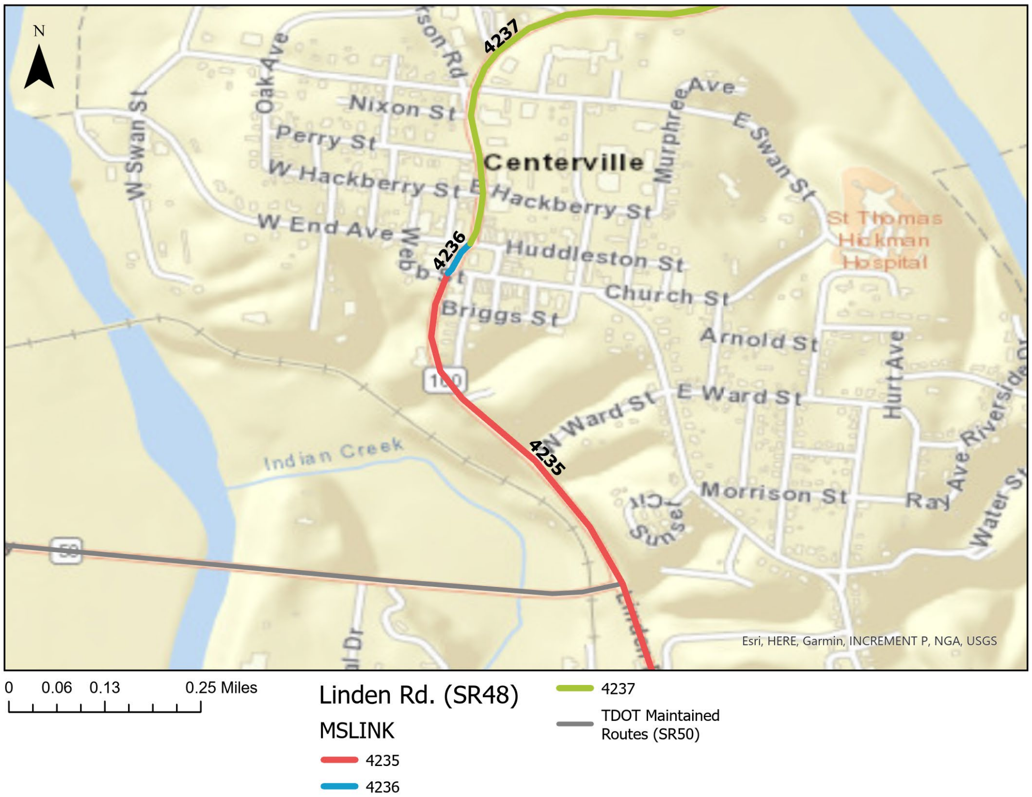


Figure 4.2.A. Illustration of fragmentation of State Route 48 through Centerville, TN into three segments (MSLINKs 4235, 4236, and 4237).

The density of WVC along the new routes was determined through spatial analysis. Distances of WVCs to routes ranged from zero to 8.3 miles with a median (heavily skewed) of 25.8 ft. Of the 4,923 route segments, 2,488 (50.5%) were null, meaning there were no associated WVC along those routes. Upon closer inspection, WVCs could be observed along roads not maintained by TDOT. This can be seen in Figure 4.2.B for WVCs 11646 and 11393 along Conner Road NE. If WVCs are selected based the median distance from a TDOT route, 18,667 (50.0%) of the 37,327 WVCs fall within this threshold. The WVC with an ID of 11349 would be selected (see Figure 4.2.B); however, WVCs 11527 and 34324 would not be selected yet can been seen having occurred on I-75 southbound. This is because TDOT maintained routes do not provide a centerline for split roads but instead represent a route with a single line.

Therefore, a closer approximation of the number of WVCs along a TDOT route was determined by including WVCs within 150 ft from a TDOT route (n=24,222). The distance of 150 ft was derived from random distance checks across the state. The 24,222 WVCs were associated back to TDOT routes based on routes' unique identifiers. Of the routes with WVCs, the minimum number of incidents was one and the maximum 131 with a median of 6. Within the highest frequency range (i.e., 97-131 using natural breaks), there are 5 routes (Figure 4.2.C). This increased to 15 routes when the second highest range (76-96) was included.

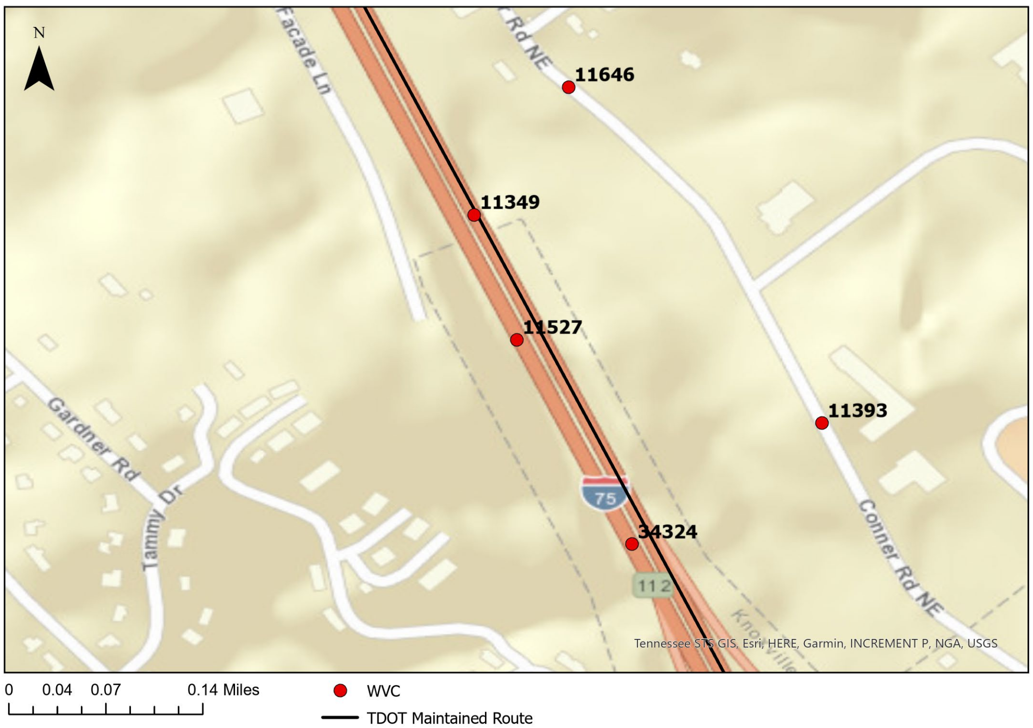


Figure 4.2.B. Placement of WVCs along Interstate 75, centered on 84.0172553°W 36.0786685°N (Northwest of Knoxville, TN).

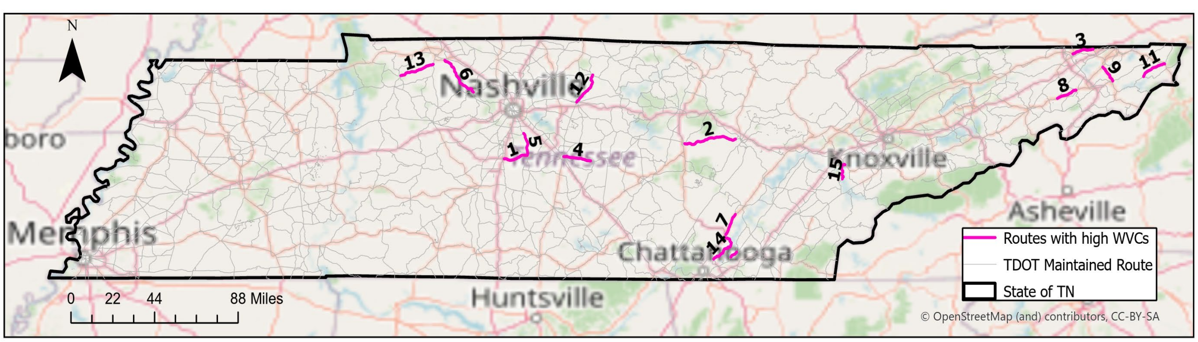


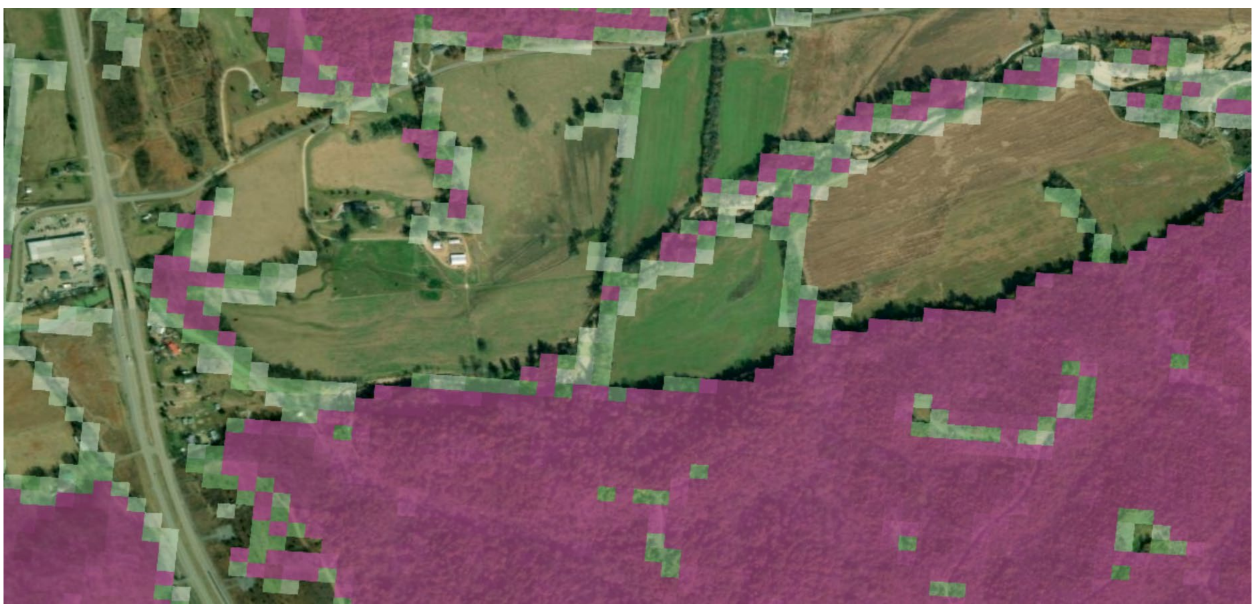
Figure 4.2.C. Location of 15 TDOT routes having the highest frequency of WVCs.

4.3 Determination of tree canopy coverage

Figure 4.3.A(a) shows an aerial image centered on 86.3411140°W, 35.8619440°N consisting of forest and crops with limited infrastructure. Figure 4.3.A(b) shows the unconditional MRCL forest layer (i.e., 1% (light green) to 100% (dark green) where the periphery of treed space adjoins agricultural cropland resulting in less density (i.e., lower percentage). After multiple iterations of investigating mid-range percentages of forest across random areas in the state and looking at known sections of forest in Shelby County, TN, a density of 55% was chosen and is shown in Figure 4.3.A(c). Two additional notes: (1) the MRCL forest layer and aerial layer for comparison were from the same year, 2021, and (2) looking at Figure 4.3.A(b) the MRCL forest layer may look to not fully capture forest such as the northern edge of the large forested area in the south, but the image was taken with the sun to the south which casts a shadow onto the crop field. However, there are other areas on the aerial image where trees or a tree line may be seen and not be covered by the MRCL. For the purpose of this project's analysis, more extensive and cohesive forest densities are desired.

(a)

(b)



(c)

Figure 4.3.A. Depiction of coverage of forest (magenta coloring) as interpreted from remote sensing by the MRCL for an example area south of Waverly, TN near the intersection of Highway 13 South and Blue Creek (86.3411140°W 35.8619440°N) showing (a) original aerial (2021), (b) overlay of MRCL forest layer density (2021) and (c) a MRCL forest density of ≥ 55%.

4.4 Characterizing Routes with High WVCs

From Section 4.2, using the two highest distributions of routes with increased numbers of WVCs, there were 15 routes identified, termed *WVC route*. A detailed characterization of these routes follows with a subsequent analysis for potential WVC reduction remediations. Six characteristics were assessed for each route (Table 4.4.1):

1. Count of WVCs
2. Number of intersections
3. Fencing
4. Culverts
5. Bridges
6. Traffic counts

Characteristics 2-5 are significant because, as will be discussed later, using fencing to direct wildlife towards a passage across a route is a foundational component, such as directing wildlife, say deer, toward a stream underpass or culvert. However, characteristic 6 (traffic counts) is discussed first.

Table 4.4.1. Characteristics of the 15 WVC routes.

			Intersections					Fencing (existing)					Culverts			Bridges			Traffic
Road ID	Route Name	# of WVC incidents	Count	# of segments	Avg. Length (ft)	Min. Length (ft)	Max. Length (ft)	# of segments	Sum Length (ft)	Min. Length (ft)	Max. Length (ft)	Avg. Length (ft)	Count	Min. Diameter (in)	Max. Diameter (in)	**O**ver **U**nder **W**ater	Divided Highway (Yes)	Closest intersection (ft)	Average Daily Count (2023)
1	I0840	88	185	67	853.3	0.9	10602.9	30	104832.8	172.5	15276.1	3494.4	---	---	---	1O:8U:1W	Yes	2626.9 | 1452.1	48442
2	SR001	107	332	161	784.1	1.3	4012.3						207	12	24	0O:1U:1W		618.3 | 786.1	5046
3	SR001	131	184	74	660.1	1.3	2002.6						55	12	36	---	Yes		19524
4	SR001	86	347	144	441.5	0.0	2910.7						126	18	48	0O:1U:1W	Yes	335.9 | 2179.8	15404
5	SR011	78	130	70	783.8	1.9	3979.8						85	12	36	---			9182
6	SR012	124	299	119	971.8	0.6	4932.8						195	12	60	0O:4U:4W		170.8 | 246.3 201.8 | 181.6 1292.2 |2415.4 84.0 | 386.2	7182
7	SR029	94	132	47	1198.8	0.8	11158.1	1	1213.2	---	---	---	46	18	30	0O:2U:2W		239.3 | 255.0 600.8 | 1414.9	14600
8	SR034	107	265	109	443.9	0.1	1698.3						67	12	36	0O:1U:1W	Yes	222.5 | 890.9	13699
9	SR037	86	129	53	824.1	0.1	2137.5	2	1103.9	528.5	575.4	551.9	43	18	30	0O:3U:0W	Yes		10512
10	SR058	79	53	17	1139.2	6.4	4312.3						53	18	24	0O:1U:1W	Yes	1788.3 | 1048.9	15540
11	SR067	79	162	66	935.1	6.7	3980.6						80	18	60	0O:3U:3W		154.7 | 384.1 55.6 | 93.0 71.6 | 283.4	4654
12	SR141	83	178	131	651.3	0.0	5176.6						183	12	48	0O:1U:1W		621.7 | 302.5 1380.7 | 914.5	6624
13	SR149	96	173	73	1119.3	4.4	4142.7						53	12	36	0O:2U:2W		1245.8 | 1825.9 648.5 | 888.4	5867
14	SR319	116	365	115	776.6	2.9	4135.8	1	636.7	---	---	---	133	12	36	1O:1U:1W		1100.8 | 683.5	3565
15	SR444	88	79	32	1422.7	14.8	5591.8						8	18	30	0O:2U:2W		1834.4 | 1167.7 1702.7 | 3468.8	10645

U=route goes over a road or river
O=route goes under a bridge(road)
W=route goes over water (bridge)

4.4.1. Traffic Counts – Characteristic #6

Traffic count data was obtained from TDOT representing daily averages for the year 2023. These data nearly coincide with the TDOT maintained route data with some situations where the *traffic* route extended further than the WVC route. For example, an off ramp may be included in the *traffic* layer where the route of interest terminates before the ramp. Hence, the traffic counts are an approximation. A scatter plot of average daily vehicle traffic to WVC is provided in Figure 4.4.1.A. Traffic counts varied along a given route. Therefore, when determining the traffic count for the WVC route, a harmonic mean was calculated as the traffic count over the segment length (see Eq. 4.4.1.e1).

$$traffic\ count\ avg = \frac{WVC\ route\ length}{\sum \frac{traffic\ count\ segment\ length}{avg\ daily\ traffic\ count}} \qquad \text{Eq. 4.4.1.e1}$$

From Figure 4.4.1.A, beyond a single outlier (Route ID:1), WVC was characterized as being independent of traffic load.

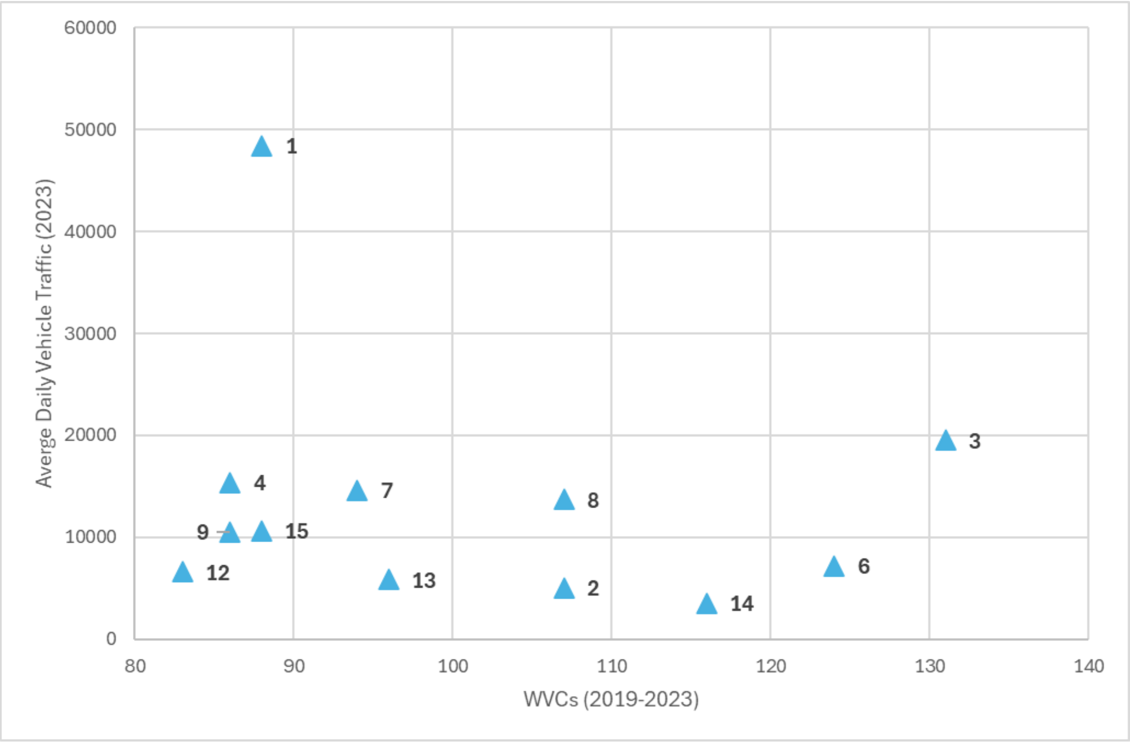


Figure 4.4.1.A. Scatter plot of average daily vehicle traffic to WVC for the 15 routes identified in Section 4.2.

4.4.2 Fencing

Of the six characteristics mentioned above in Section 4.4, characteristics 2-5 were included because research has shown that fencing alone can reduce WVCs by 80-99% (Huijser et al 2008; Clevenger et al. 2001), especially in combination with other factors. TDOT maintains a database of fencing along its maintained routes. Of the 15 WVC routes, four had fencing. Route ID 1 had the most liner footage of fencing, totaling 104,832.8 ft (~20 miles) consisting of 30 segments. Route IDs 7, 9, and 14, had much shorter lengths at 1213.2 ft, 1103.9 ft, and 636.7 ft, respectively, with Route ID 9 consisting of 2 segments. Though metadata on fence height was not available to the research team, it is assumed that the fencing is of standard construction for separation between a TDOT route and adjacent land; hence, it is not at a height necessary to prevent large mammals (i.e., deer and elk) from jumping the fence line. Fence heights should be over 8 ft tall to prevent overtopping (Gulsby et al., 2011). One could consider adding/replacing fence; however, linear distances also play a factor (see following sections).

4.4.3. Intersections

Fencing along routes can serve to direct deer to an engineered crossing as a mitigation approach. One factor to consider is the length of fencing both for effectiveness and cost/benefit. Fencing length is governed by entrances to the route, such as at road intersections and driveways. To determine these structured breaks along each route, the State of TN e911 road centerline dataset was used to create intersection points along each WVC route. A challenge arose where WVC routes, as derived from the TDOT maintained route dataset, was not centerline-based such when routes were divided highways, only one direction was represented in the TDOT route database (see Table 4.4.1 Bridge – Divided Highway). Therefore, intersections from the e911 dataset were used to split the WVC route based upon shortest distance between the two data.

When split, the 15 WVC routes became subdivided into 1,019 segments. Upon inspection of the longer segments (> 10,000 ft) for possible fencing, it was observed that driveway entrances existed along the segments which would result in further subdivision. As TDOT does not maintain a driveway data layer, a visual inspection of each WC route against aerials was required. An arbitrary segment length of one mile (5280 ft) was chosen and each segment (n=18) inspected for driveways and the segments were split.

Driveways were determined to be of great importance when assessing routes for potential fencing. For example, of the 18 segments greater than one mile in length, SR141 (Route ID: 12) had a segment at 13,061.8 ft. After splitting this one segment at driveways, it became subdivided into 26 segments with none longer than a mile. After visually inspecting the 18 longer segments, only 3 (0.23%) segments remained longer than a mile. Table 4.4.1 presents the results of intersection WVC routes with roads and driveways.

It could be considered that divided highways may have an uninterrupted length in one direction versus the other, but this could not be captured following the splitting procedure above. Still, long, interrupted route lengths say nearly a mile or longer, were observed along Route IDs 1, 7, and 15 with maximum lengths of 10602.9 ft, 5667.2 ft, and 5591.8 ft, respectively. Other divided highways had lengths shorter than a mile. A "mile" is an arbitrary length used as a threshold here. If, for divided highways, longer lengths were present in a particular direction, fencing off in one direction while not the other could trap large mammals on the interior fence side, providing greater harm to drivers. Addressing whether fencing could guide mammals to a crossing point follows the next two sections.

4.4.4 Culverts

Culverts can serve as passageways for animals to pass beneath roadways; however, there are several conditions (e.g., physical dimensions, construction materials, lighting, water depth) that must be met for them to utilize this passage with each animal type having different preferences/requirements. Smaller animals (e.g., turtles, raccoons, rabbits, fox, bobcat) are more likely to pass through small culverts (<24 inches) (Brunen *et al.*, 2020). USDA (2024) suggests that a minimum height for larger animals like white tailed deer and elk be 8 ft (96 inches).

Several culverts (n=1,334) exist along WVC routes except for I0840 (zero culverts) (i.e., I-840) and SR444 (8 culverts). The larger sizes were 48 to 60 inches (assuming all were round), representing 8 (0.6%) of the 1,334 culverts. Of these eight, only one seemingly crosses the main thoroughfare (i.e., observed on aerials) with the remaining seven crossing under non-maintained TDOT laterals or driveways. Considering the shape of the culvert, white-tailed deer are prone to use drainage box culverts (Sparks and Gates 2012). Smaller culverts (e.g., 48 in x 48 in box) have been shown to be used by black bear (Jensen et al. 2018).

4.4.5 Bridges

Fencing has been used effectively to herd mammals (e.g., deer) towards river underpasses, (Donaldson et al. 2016). Even without fencing underpasses are natural pathways taken by animals (Foster 1995). Another bridge alternative is to create a wildlife bridge over a roadway. These wildlife bridges are preferred by large mammals such as deer and elk (Huijser et al. 2008; Simpson et al. 2016).

An analysis was performed on the presence of bridges (overpass and underpass) for each WVC route. From Table 4.4.1, Route IDs 3 and 5 had no bridges. For the other routes, counts of overpasses (O), underpasses (U), and underpasses with water (W) were recorded based on aerial imagery. For example, a route with 1 overpass, 8 underpasses and of those 8 underpasses one was a waterway, the coding would be 1O:8U:1W (see Table 4.4.1 Bridges Route ID 1). Additionally, the distance from the bridge to the closest intersection in both directions was measured for consideration of fencing distances. Therefore, for Route ID 1, the closest intersection in one direction was 2626.9 ft away and in the opposite direction 1452.1 ft away. In instances when more than one underpass was a waterway, distance measures to intersections were made at each bridge (see Table 4.4.1 Bridges Route ID 6 with four waterways).

All overpasses were roads; hence, none would serve as wildlife corridors – wildlife corridor overpasses are often converted bridges or purposely constructed for the sole purpose of wildlife. Only Route ID 1 had multiple underpasses (eight) with only one being a waterway. The seven underpasses were roads. For the remaining waterway underpasses, distances to the closest intersection ranged from 55.6 ft (Route ID 11) to 3468.8 ft (Route ID 15).

4.5 Environmental Conditions

The TDOT WVC database contained two environmental condition categories: lighting and weather, as represented in Figures 4.5.A and 4.5.B, respectively. Lighting consisted of eight conditions ranging from lighted to dark to somewhere in between. The largest number of WVCs occurred in dark, unlit conditions (49.2%) while the second most common lighting condition was daylight (29.2%). Dark (lighted or not) occurred mostly during the evening as illustrated by the range of times against a 24-hour clock; however, conditions of “dark” after 7:30 PM are questionable unless it was extremely overcast (why not “cloudy” to match attribute value) or in error. According to sunrise data for Memphis, Nashville, and Johnson City during December (winter) for the arbitrary year of 2021, sunrise occurred between 6:45 AM and 7:40 AM. However, the condition of lighting outside common-sense norms were considered outliers as they represented a fraction of a percent of the records (e.g., dark past 8 AM was 0.05%). Weather conditions included 12 categories with the majority by rank being clear, cloudy, rain, unknown, fog, and snow (99.9%). Clear conditions represented 77.8% of WVC weather conditions followed by cloudy at 11.3%. Interestingly, taking into consideration that wet roads require extra caution due to increased stopping time and potentially decreased visibility, only 6.4% of incidents occurred during the “rain” weather condition.

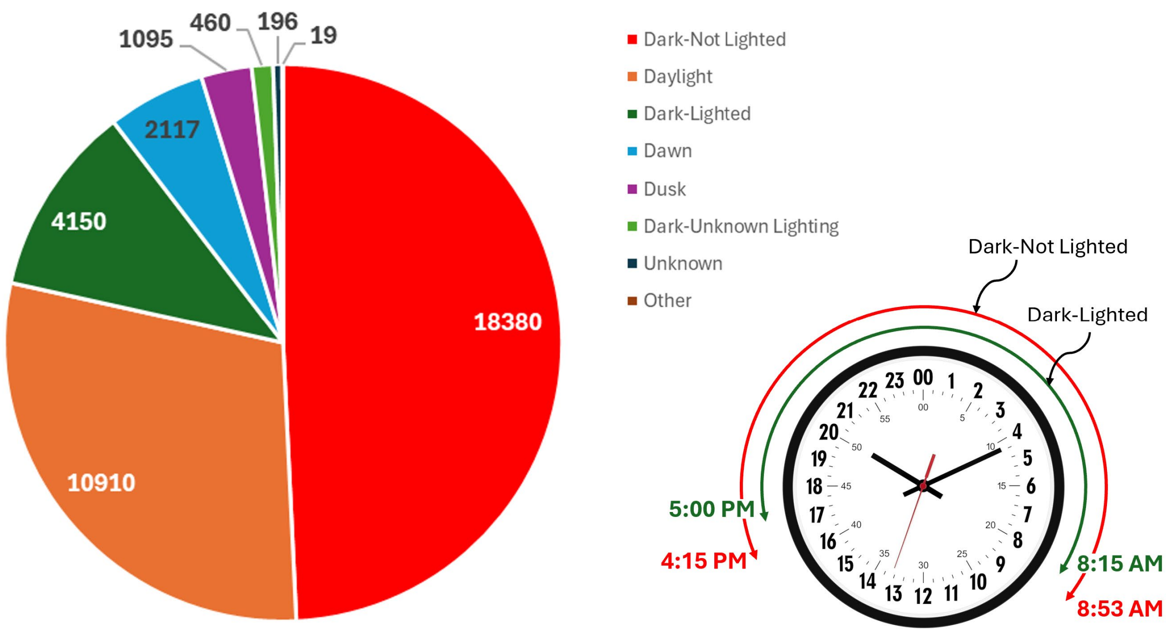


Figure 4.5.A. Number of WVC lighting conditions for all TDOT WVCs (n=37,327) between 2019 and 2023.

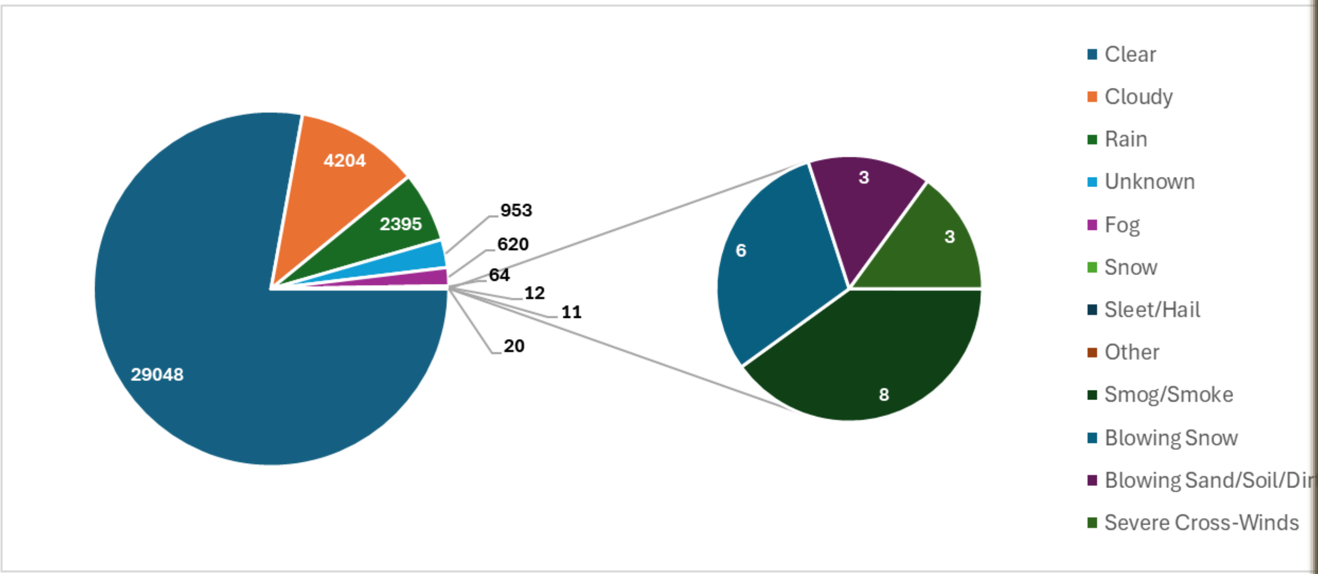


Figure 4.5.B. Count of WVC weather conditions for all TDOT WVCs (n=37,327) between 2019 and 2023.

When considering time of day, Figure 4.5.A suggests a majority of WVCs occur between 4:15 PM and 8:53 AM. Time-of-day WVCs were further broken down by hour with more frequent WVCs occurring in the morning hours between 06:00 and 08:00 AM and the evening hours of 18:00 and 22:00 PM. During the peak of daylight (i.e., 11:00 AM to 3:00 PM), WVCs were considerably less frequent (7.8% of total WVCs).

4.6 WVC Temporal Analysis

WVC data (n=37,327) was obtained over the period 2019 to 2023 (5 years). Two temporal analyses were performed: (1) distribution of WVC by year and (2) cumulative monthly distributions of WVC over the 5-year period. Annually, accumulation of WVCs ranged between 6827 and 8194 with very little variation year-to-year although declining (Figure 4.6.A).

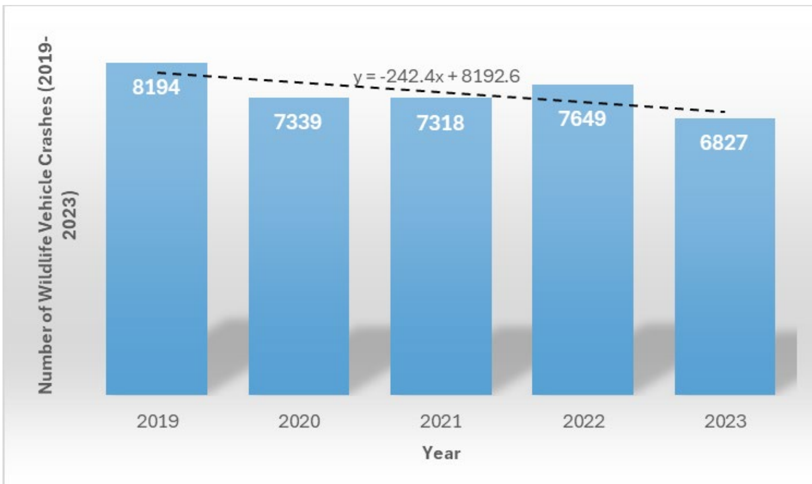


Figure 4.6.A. Annual WVC counts between 2019 and 2023 showing a decline in incidents with a slope of -242.4.

A summation of WVC incidents by month showed a notable rise in WVCs in November with a leading up to and decline from that month (Figure 4.6.B). This is to be expected as deer, which comprise 84.9% of the WVCs, rut around the November timeframe, being much more active (Bashore et al. 1985; Bissonette et al. 2008; Stickles et al. 2022).

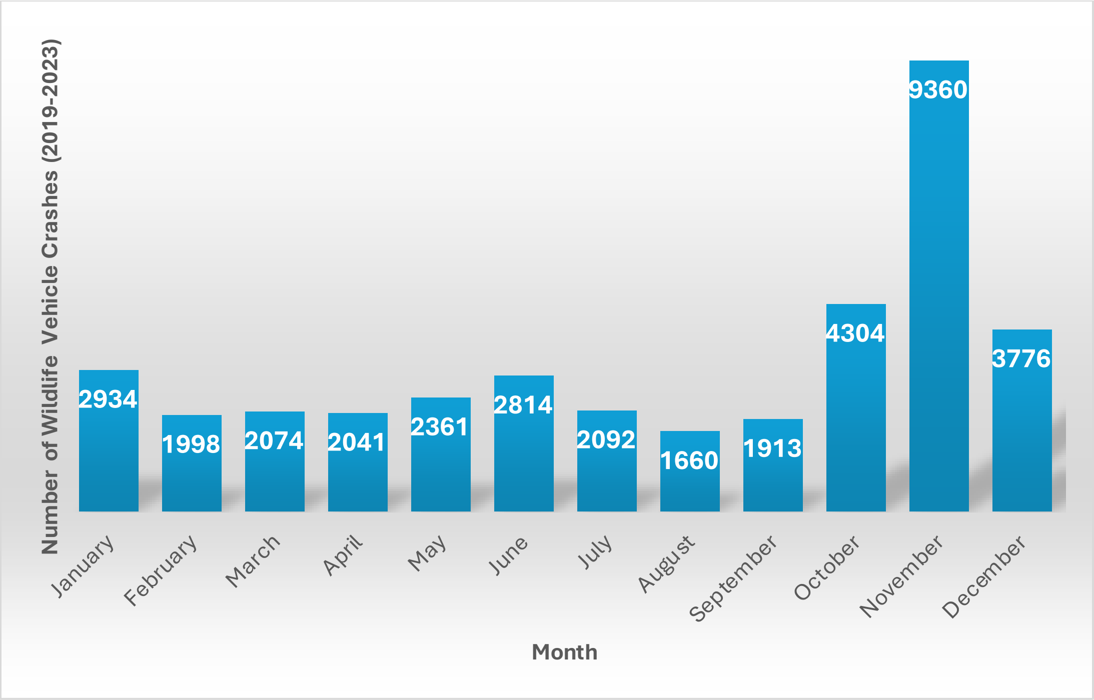
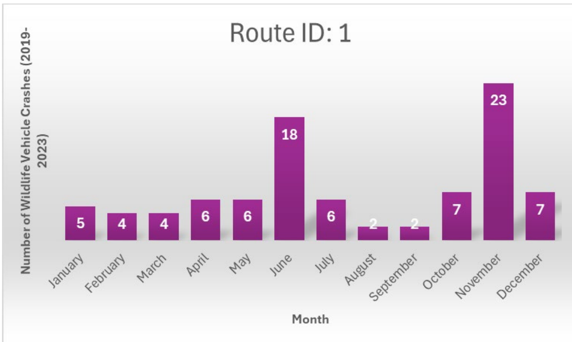


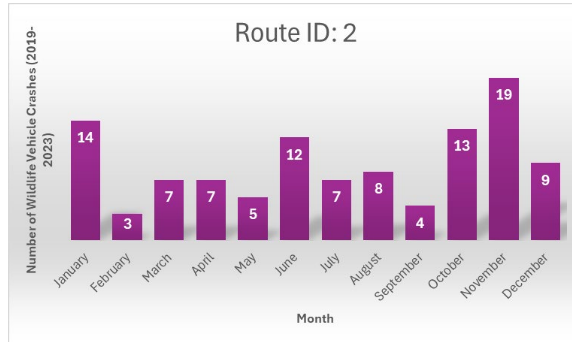
Figure 4.6.B. Summation of WVCs by month (numbers in white) between 2019 -2023.

Figures 4.6.A and 4.6.B reflect overall trends in the WVC data statewide. Detailed temporal analyses were conducted for the 15 WVC routes. Figure 4.6.C indicates the number of WVCs for each WVC route during the period 2019-2023. A few routes standout as having a higher number of WCS year-to-year, those being Route IDs 3, 6, and 15. Notable lows in WVCs were Route IDs 1, 4, 11, and 12. Also depicted on Figure 4.6.C are the slopes from a linear regression of the 5 years of WVCs for each WVC route. Route 3 (high WVCs) does not show a change across the years (i.e., slope = 0.0). This differs from the other two routes with notably higher WVCs, Route IDs 6 and 15, which show declines having slopes of -1.0 and -5.2, respectively. Routes 1 and 4 varied little (i.e., slopes < 0.1) where Route IDs 11 and 12 showed declines with slopes of -1.1 and -0.8, respectively. Route ID 8 had the greatest increase (slope = 0.6) followed by Route ID 2 (slope = 0.5).

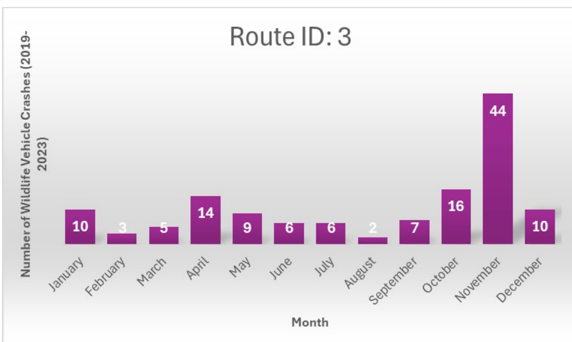
A monthly summation of WVCs for each WVC route are shown in Figure 4.6.D. All WVC routes had similar highest WVC incidents in November; however, six WVC Routes (Route IDs 1, 4 (slight), 6, 9, 11, and 15) had increased incidents during June (see Figures 4.6.D.[a, d, f, i, k, o]). Route ID 2 also showed a peak in June (n=12) and also in January (n=14) which had a WVC count second highest to November (n=19) (see Figure 4.6.D.b). Both Route IDs 7 and 8 had minimal incidents throughout the year except for November where incidents were 854% and 717% higher than the yearly average of the other months. By proximity, Route ID 7 is in middle TN and Route ID 8 is in east TN.


Route ID: 1
Number of Wildlife Vehicle Crashes (2019-2023)
5
4
4
6
6
18
6
2
2
7
23
7
January
February
March
April
May
June
July
August
September
October
November
December
Month

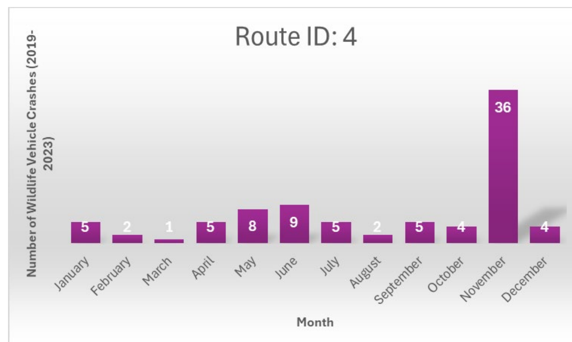
(a)


Route ID: 2
Number of Wildlife Vehicle Crashes (2019-2023)
14
3
7
7
5
12
7
8
4
13
19
9
January
February
March
April
May
June
July
August
September
October
November
December
Month

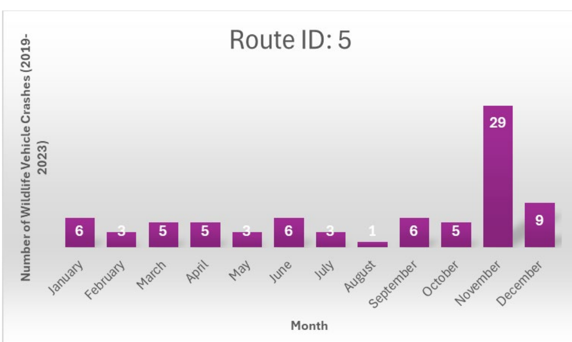
(b)


Route ID: 3
Number of Wildlife Vehicle Crashes (2019-2023)
10
3
5
14
9
6
6
2
7
16
44
10
January
February
March
April
May
June
July
August
September
October
November
December
Month

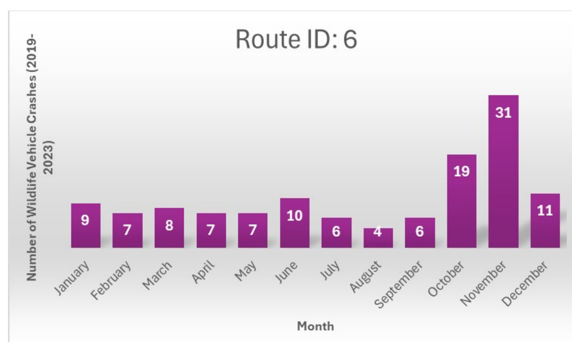
(c)


Route ID: 4
Number of Wildlife Vehicle Crashes (2019-2023)
5
2
1
5
8
9
5
2
5
4
36
4
January
February
March
April
May
June
July
August
September
October
November
December
Month

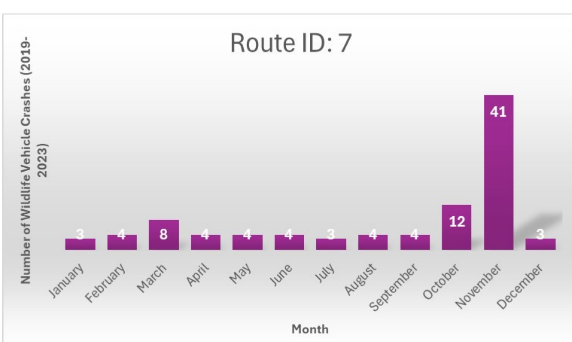
(d)

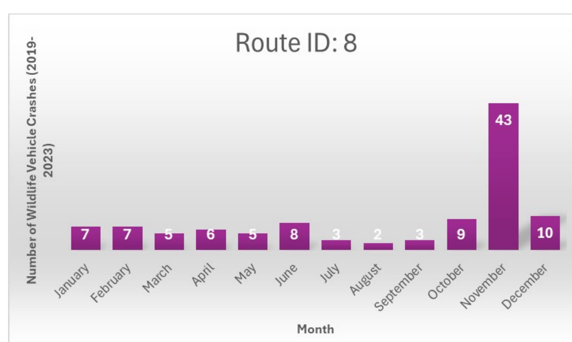

Route ID: 5
Number of Wildlife Vehicle Crashes (2019-2023)
6
3
5
5
3
6
3
1
6
5
29
9
January
February
March
April
May
June
July
August
September
October
November
December
Month

(e)

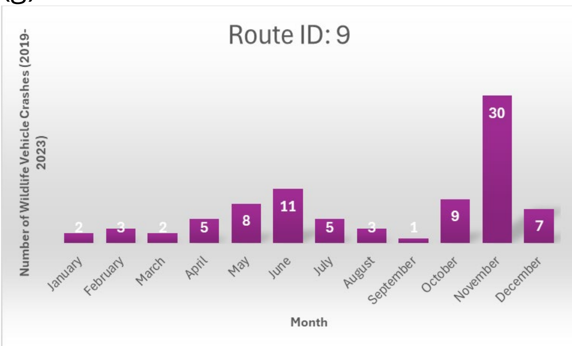

Route ID: 6
Number of Wildlife Vehicle Crashes (2019-2023)
9
7
8
7
7
10
6
4
6
19
31
11
January
February
March
April
May
June
July
August
September
October
November
December
Month

(f)

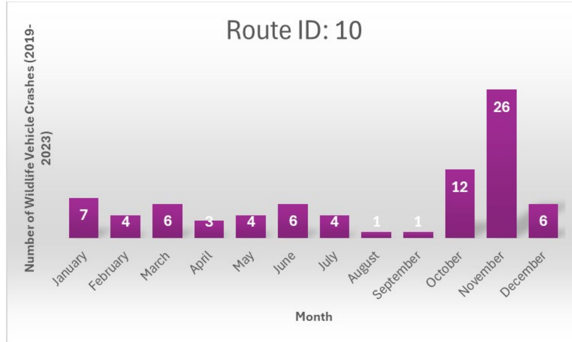

Route ID: 7
Number of Wildlife Vehicle Crashes (2019-2023)
3
4
8
4
4
4
3
4
4
12
41
3
January
February
March
April
May
June
July
August
September
October
November
December
Month


Route ID: 8
Number of Wildlife Vehicle Crashes (2019-2023)
7
7
5
6
5
8
3
2
3
9
43
10
January
February
March
April
May
June
July
August
September
October
November
December
Month

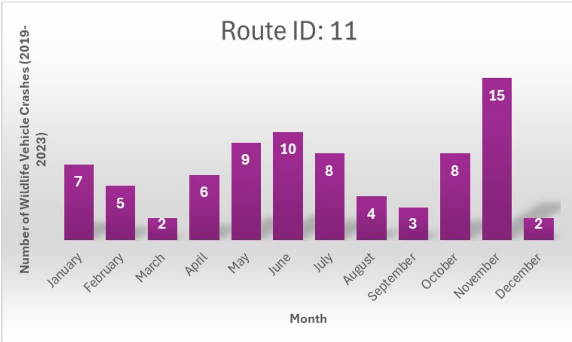
(g)


Route ID: 9
Number of Wildlife Vehicle Crashes (2019-2023)
2 3 2 5 8 11 5 3 1 9 30 7
January February March April May June July August September October November December
Month

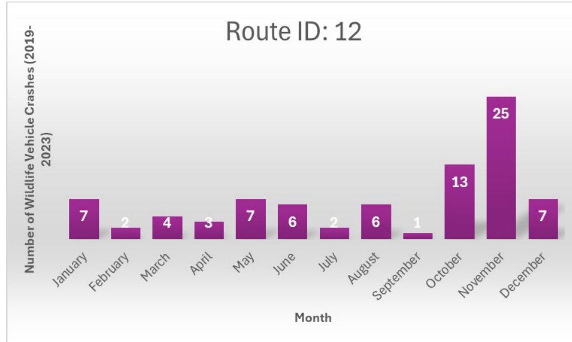
(h)


Route ID: 10
Number of Wildlife Vehicle Crashes (2019-2023)
7 4 6 3 4 6 4 1 1 12 26 6
January February March April May June July August September October November December
Month

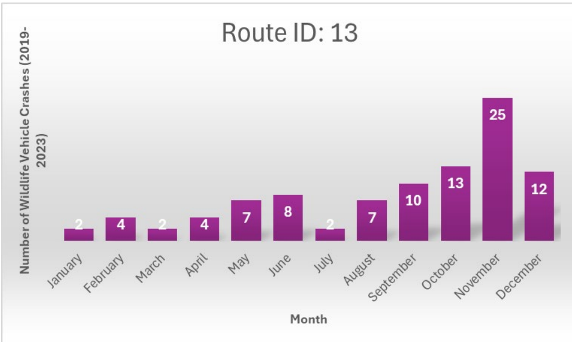
(i)


Route ID: 11
Number of Wildlife Vehicle Crashes (2019-2023)
7 5 2 6 9 10 8 4 3 8 15 2
January February March April May June July August September October November December
Month

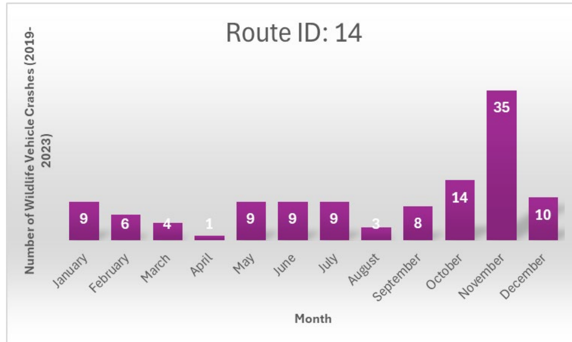
(j)


Route ID: 12
Number of Wildlife Vehicle Crashes (2019-2023)
7 2 4 3 7 6 2 6 1 13 25 7
January February March April May June July August September October November December
Month

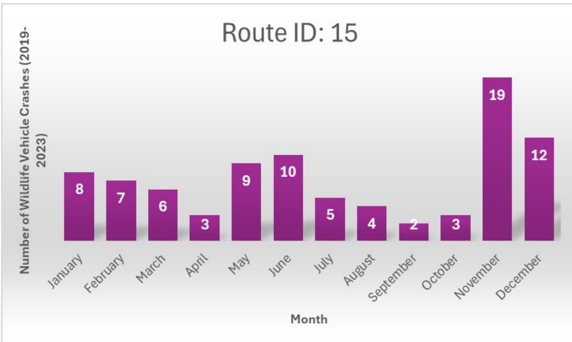
(k)


Route ID: 13
Number of Wildlife Vehicle Crashes (2019-2023)
2 4 2 4 7 8 2 7 10 13 25 12
January February March April May June July August September October November December
Month

(l)


Route ID: 14
Number of Wildlife Vehicle Crashes (2019-2023)
9 6 4 1 9 9 9 3 8 14 35 10
January February March April May June July August September October November December
Month

(m)


Route ID: 15
Number of Wildlife Vehicle Crashes (2019-2023)
8 7 6 3 9 10 5 4 2 3 19 12
January February March April May June July August September October November December
Month

(n)

(o)

Figure 4.6.D. WVC counts by month for the 15 WVC (a-o) routes (2019-2023).

4.7 Proximity to External Factors

Habitat criteria are important when ascertaining where mitigation structures should be implemented (Hurley et al. 2009). Much of Tennessee is rural with a patchwork of forested and open land. Interestingly, forested habitats with increased forest-field edge densities have been associated with increased deer-vehicle collisions (Gunson et al. 2011; Huijser, M. et al. 2008; Farrell and Tappe 2007; Bashore et al. 1985). A spatial analysis was performed using the MRCL forest layer (≥55% - see Section 4.3) and the TDOT maintained routes to determine the %-length of roads that had forests within 200 ft and the count of WVCs proximal to those sections. The 200 ft distance is somewhat arbitrary though chosen slightly further than 150 ft for assessing WVCs. The literature review (Appendix A) did not reveal a distance between road and forest edge although Gulsby et al. (2011) found that fences between approximately 100 ft to 410 ft within forest conditions reduced WVCs involving deer. A subsequent spatial analysis was performed on the 15 WVC routes. To capture *more substantive* forested areas, forest areas below one standard deviation from the mean area were removed from the analysis (a 96.4% reduction in number of polygons but a 4.90% reduction in total area).

To better isolate forest fragmentation associated with specific road lengths, the TDOT routes (n=4,923) were densified into ten-mile segments resulting in 217,550 segments (mean length = 498.0 ft). Of these segments, 105,556 had forest within 200 ft, representing 45.9% of the TDOT maintained route road miles. The number of WVCs within 150 ft of these proximal forest/forest-field segments was 11,910 (31.9%). This would suggest that forest/forest-field conditions do not substantively contribute to WVCs. However, when analyzing the WVC routes, 62.5% (nearly double) of the WVCs are attributed to forest/forest-field conditions.

Other spatial factors investigated were lands designated for hunting, state parks/natural areas, municipal parks, and recreation areas. Within 0.25 miles of these areas, there were 1,033 (2.8%) WVCs. When extending the search radius to a half mile, the count of WVCs increased to 6,478 (17.4%).

5.0 Discussion

Between 2019 and 2023, there were 37,327 WVCs related directly to animals based on records obtained from an AASHTO database. With the majority of the WVCs being deer, an attempt was made to reason why they occurred by tying them to population density. It was speculated that the presence of higher deer population centers would correlate to WVCs; hence, reinforcing the likelihood of increased WVCs in those locations. Such correlations were attempted by others using county-scale data from hunting records. TWRA monitors wildlife conditions statewide; unfortunately, they do not conduct localized population surveys of animals such as deer, elk, turkey, etc. Conversations were held with TWRA on the possibility of them providing a survey to their constituency to determine potential populations, but they had just completed a survey on a different issue and were understandingly unwilling to issue a subsequent survey. However, there was expressed interest in including population questions in future surveys. Nonetheless, TWRA provided their hunting counts (2019-2023; n>1.2 million records) for this study to serve as a proxy for living populations. A vast majority of the records only listed the county name as its spatial reference (polygon). However, 321,434 hunting occurrences were associated with a longitude and latitude. Creating a heat map of WVCs and merging with the hunting data, three high population centers were identified – the largest population was centered in Clarksville, TN.

An alternative spatial analysis was performed by merging WVC counts along TDOT-maintained routes (incidents within 150 ft). When comparing WVC route densities to the population heat map, they did not match. TWRA reasoned that their data point records may not be actual locations where the animal was killed, but the location of the person at the time of entry which very well could be the individual's residence. Investigating this further, WVCs were seen to be in highly urbanized neighborhoods at individual homes. Furthermore, the TWRA dataset originally included 366,855 hunting occurrences with coordinates, but after deeper inspection, 45,421 records were located at one of two locations in downtown Nashville; thus, the data was suspected of being entered at TWRA office locations by TWRA personnel. Not knowing the true spatial accuracy of this TWRA point data, it was not used in subsequent analyses and the WVCs associated with TDOT routes were relied on for the analysis instead.

An extensive literature review was conducted on the occurrence, causes, and mitigation approaches for WVCs. The findings from the literature review helped guide analyses on Tennessee's WVCs for this study and to inform decisions on mitigation alternatives. This literature review was conducted under this project by three individuals at the University of Georgia in Athens, GA and is provided in Appendix A.

WVCs are common occurrences, but certain mitigation strategies that consider animal behavior have proven effective in reducing WVCs. For example, deer are more active during rutting which peaks in November (see Figure 4.6.B), they tend to use combined forest +field habitats for feeding and safety, and they can shimmy under fences or jump over them. Mitigation measures include tall fencing (≥ 8ft) (Gulsby et al. 2011, Donaldson et al. 2016) that extend for long distances (preferably > 3 miles) (Huijser et al. 2016), and terminate at junctions that prompt safe and *welcoming* (i.e., size, openness, structural material, lighting, entrance/exit conditions, wet conveyance, etc.) passage such as underpasses (Ng et al. 2004, Gordon and Anderson 2003, Clevenger and Waltho 2000), overpasses (Brennan et al. 2022, Simpson et al. 2016, Huijser et al. 2008, Clevenger and Waltho 2005), and drainage culverts (Brunen et al. 2020, Sparks and Gates 2012, (Donaldson 2007, Clevenger et al. 2001). In addition to these factors, others may include vehicular traffic and speed, lighting (natural or otherwise), time of day, and weather.

Considering first these four latter factors, TDOT traffic counts (2023 daily averages) were associated with route WVCs. Apart from one outlier (Route ID 1), WVCs were not considered dependent on traffic count, similar to conclusions by Bissonette and Kassar (2008) and Waring et al. (1991). When considering lighting, of the 37,327 WVCs in Tennessee during the period 2019-2023, the majority of WVCs (60.4%) occurred under dark or dark-lighted conditions (see Figure 4.5.A). This aligns with Wilkins et al. (2019) who estimated 70% of WVCs occurred in dim/dark conditions. The next largest lighting category was daylight at 29.2%. It may be that WVCs occurred more under darkened lighting because drivers would not easily see the approach/presence of wildlife (Stickles et al. 2022). Breaking down the lighting further, considering time of day, dawn and dusk are times when WVCs are elevated. Based on WVCs for Tennessee, morning periods between 6:00 and 8:00 AM and 6:00 and 10:00 PM had the highest frequency of WVCs, or 20.4% (n=7,633) and 35.7% (n=13,337), respectively. Based on the literature (see Appendix A – Timing), elevated WVCs occurred between 4:00-9:00 AM and 5:00-10:00 PM (Wilkins et al. 2019, Huijser, et al. 2008, Dodd et al. 2007) with some of these ranges expanded in other studies. Lastly, there was the consideration of weather. In Tennessee, the large majority of WVCs occurred during clear conditions (77.8%). The second most common weather condition was cloudy at 11.3% followed by rain (6.4%). The literature review did not examine weather conditions in detail, instead grouping clear and cloudy conditions as non-impactful to driving. In contrast, rain and snow/ice accounted for nearly 90% of WVCs, suggesting that poor weather should not be viewed as a major contributing factor to these collisions.

When considering the other factors (overpasses, fences, drainage culverts, etc.), these are more strongly associated with mitigation strategies. Fencing serves as a foundation for many physical mitigation strategies by directing animals towards passages that avert them from crossing the road. The analyses regarding these factors were performed on the 15 WVC routes. The first to be discussed are bridges. Only two bridges under consideration are overpasses. When considering an overpass for wildlife passage, it is a bridge dedicated to that purpose and does not include vehicular or pedestrian traffic. The two overpasses found in this study area along WVC routes are roads. Therefore, they are not a feasible option for conversion to a wildlife overpass as a mitigation technique. Of the many bridges that allow for water conveyance (i.e., streams), most are bracketed by nearby intersections with only one intersection more than half a mile away (Route ID 15 – see Table 4.4.1) which reduces the potential for successful mitigation due to the short distance of fencing that would be possible to direct wildlife to the water conveyances as a roadway crossing mechanism. The remaining underpasses were roadways rendering them unusable for wildlife passages.

Of the 1,334 culverts, the largest were 48 or 60 inches in diameter with only one crossing beneath a WVC route. This dimension and smaller (24-inch) may suffice for smaller wildlife like bobcat and skunk (Chen et al. 2021). Black bears may also use culverts at 48 inches, but the dimensions provided by Jensen et al. (2018) suggest a box culvert (16 ft^2), not circular (12.6 ft^2). Culverts alone were not typically enough to encourage wildlife to use them but could be effective if combined with fencing (Brunen et al. 2020).

Ultimately, tall fencing (>8 ft) serves an effective means of directing wildlife to alternate passages to avoid roadway crossings. Unfortunately, a major hinderance to using fences is the presence of entryways (e.g., driveways, field access roads, utility roads) that break up fencing into segments that reduce their effectiveness. Additionally, differences in fencing lengths on opposite sides of a road can lead to entrapment of wildlife that could refocus their activity back onto roadways. Only WVC routes 1, 7, and 15 had extended, unbroken (i.e., no entryway) lengths longer than a mile.

For the 2-mile segment of Route ID 1, there were 14 WVCs between 2019-2023 with no more than three incidents in any given year, none resulted in fatalities. This is the only WVC route that has TDOT fencing, though it is only approximately 3 ft high (Figure 5.0.A). At the western end, fencing terminates at a road underpass where I-840 goes over Harpeth School Road (Figure 5.0.B(a)). Any funneling of animals at this location could guide them under the bridges on the eastern side to avoid animals entering Harpeth School Rd (Figure 5.0.B(b)). However, at the eastern end, I-840 includes on/off ramps to Peytonsville-Trinity Road (Figure 5.0.C) which does not offer secluded passage without directing animals onto the crossroad.

Figure 5.0.A. TDOT fencing along Route ID 1 (Interstate 840) eastbound at 86°49'2"W 35°49'12"N (Google Streetview August 2023).

(a)

(b)

Figure 5.0.B. Westend of I-840 at junctionwith Harpeth School Rd (86°49'9"W 35°49'14"N) showing (a) the underpass (Imagery 2025 Airbus, Maxar Technologies) and (b) the vegetated east side of Harpeth School Rd looking north (Google Streetview April 2023).

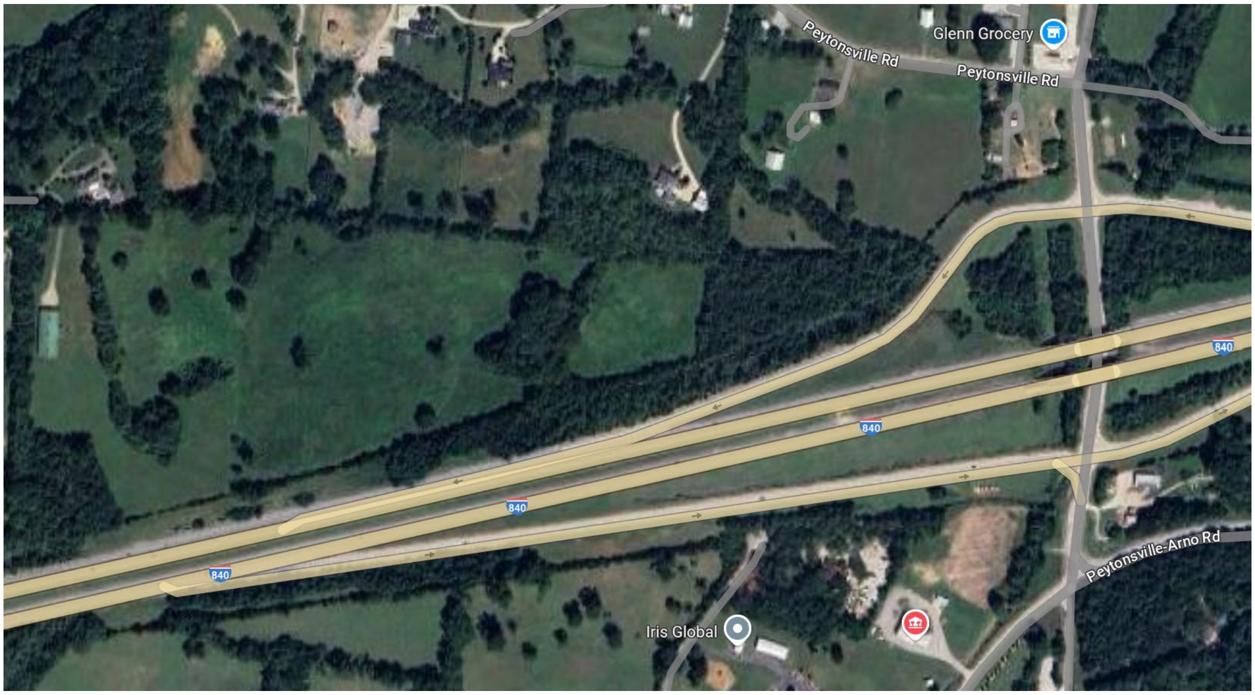


Figure 5.0.C. East end of I-840 at Peytonsville-Trinity Rd. underpass depicting the off/on ramps (86°44'51"W 35°49'21"N) (Imagery 2025 Airbus, Maxar Technologies).

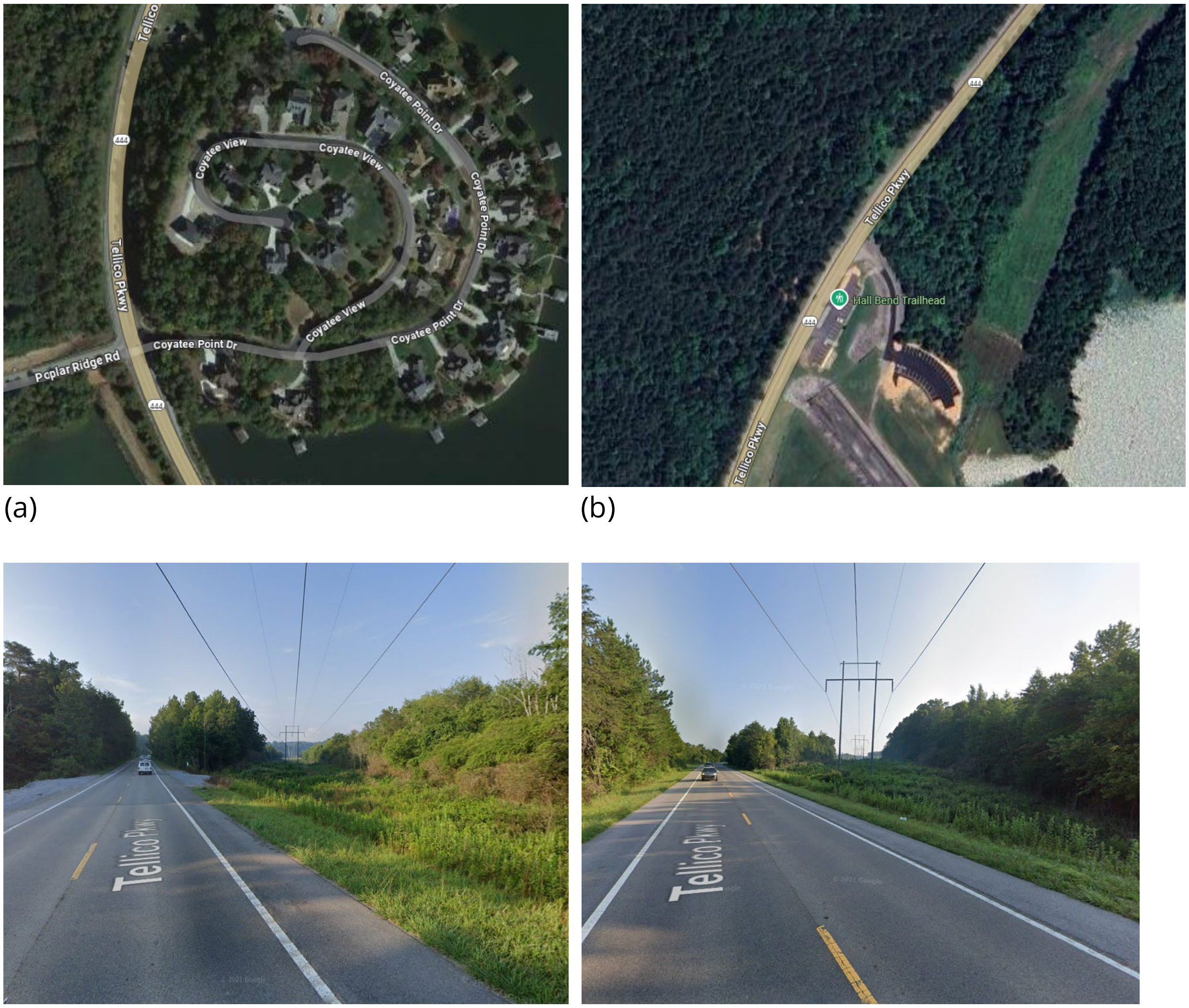
For the 1.1-mile segment of Route ID 7, there were 8 WVCs between 2019-2023 with three incidents each year except in 2019 and 2020 when there were one during each, none resulting in fatalities. The segment is defined by at-grade driveways (Figure 5.0.D). The road is bordered by forest forming up to the shoulders. Private property boundaries, derived from State of TN parcel data, are between 10-50 ft from the road shoulder. This proximity of forest to road may warrant not providing fencing. Puglisi et al. (1974) suggested that WVCs increased when fencing was installed at edge habitats or under 75 ft from forested environments where both conditions are true along this 1.1-mile segment. Interestingly, at the southern end of the segment there was a grouping of four WVCs (30.1%) which, if fencing was installed, would focus on animal traffic at fencing termination.

(a) (b)

Figure 5.0.D. Depiction of driveway entrances at the ends of a 2.1-mile segment of Route ID 7 (State Route 29 or Dayton Pike) at its (a) southern and (b) northern ends, centered on 35°24'58.0"N 85°05'52.0"W. (Imagery 2025 Airbus, Maxar Technologies)

Route ID 15 has a 1.1-mile segment; however, the driveway at the south end is a pullout (Figure 5.0.E) and if fencing were to skirt the edge of that turnout, the next driveway is another 2,129.3 ft further south at a small community of homes (Coyatee Point) along the reservoir shoreline, making the total fence-able length 1.5 miles. Using this length, there were 12 WVCs between 2019-2023 with five recorded incidents in 2020, four in 2021, two in 2022, and one in 2023, none resulting in fatalities. The segment is defined by at-grade driveways (Figure 5.0.F(a-b)). The road is mostly bordered by forest forming up to the shoulders; however, a powerline easement (grass and low bushes cross the road near the northern intersection (~550 ft) (Figure 5.0.F(c-d)) and the Tellico Reservoir forms up along the east. Many of the private parcel boundaries are between 50-60 ft from the road shoulder. At-grade intersections with fence terminations could result in animals being caught within the fenced perimeter should they stay within the road corridor. At the south end of Route ID 15 segment, two WVCs were recorded in the intersection, one in 2020 and the second in 2022.

Figure 5.0.E. Location of pull-out on State Route 444 (Tellico Pkwy) (84°15'37"W 35°44'18"N). (Imagery 2025 Airbus, Maxar Technologies)



(a) (b) (c) (d)

Figure 5.0.F. Depiction of driveway entrances at the ends of a 1.1-mile segment of Route ID 15 (State Route 444 or Tellico Pkwy) at its (a) southern and (b) northern ends, centered on 84°16'3"W 35°45'54"N and the (c) southbound easement condition and (d) northbound easement condition. (Imagery 2025 Airbus, Maxar Technologies)

Routes IDs 1, 7, and 15 all had extended length of road (> 1 mile) that were investigated for possible fencing. However, Huijser et al. (2016) suggested continuous lengths of >3 miles are advantageous for reducing WVCs. Even if fencing was an option on these segments, only Route 1 offers possible passage at its west end at the overpass with Harpeth School Rd.

All other fencing terminations would focus animal crossings at at-grade crossings with the roads. One may think of placing an animal crossing sign at these outlets, yet Sullivan and Messmer (2003) found that such permanent signage was not a cost-effective measure in reducing deer crossings due to human habituation. Outside of the 15 WVC routes, other routes of lesser WVC incidents were randomly reviewed to assess fencing options in consideration of driveway entrances. For WVC frequencies between 58-76 (n=25), many had driveway entrances and in some observed cases WVC incidents were clustered in sections with numerous driveways, meaning fencing would not be of help. Four of the routes were interstates and the remainder highways.

One TDOT route, Interstate 40 between Bobo Rd. and Opossum Hollow Rd. (length≈7 miles; 24 WVCs) had no entrances and two stream crossings (Figure 5.0.G). Although the WVC count is over a third lower than the lowest incident range for the 15 WVC routes (76 WVCs), longer road segments along major interstates may provide potential fencing opportunities. Wilkins et al. (2019) suggests that the cost-benefit ratio for WVC mitigation strategies, such as underpasses (C/B ratio=3.0) and fencing (C/B ratio=30), outweigh any perceived disadvantages. Two of the remaining three interstates (WVC frequency of 58-76) were sections of I-26, one in Kingsport, TN and the second running north out of Erwin, TN (both in east TN) where upon inspection of aerials, they did not have any lengths approaching 2 miles. The last interstate segment, I-24 between could be divided into two segments: (1) between the entry ramps at Highway 76 and Dixie Bee Rd. (length=4 miles) and (2) between Dixie Bee Rd. and Maxey Rd. (length=3.83 miles); however, the end points to any fencing would be onto roads including I-24 at the interchange with Highway 76.

(a)

(b)

Figure 5.0.G. Two stream crossings (aerial and Google Streetview) on the I-40 segment at (a) mile marker I-40 West 245.2 and (b) near mile marker I-40 West 250.0. (Aerial: Imagery 2025 Airbus, Maxar Technologies; Google Streetview Dec. 2024)

When considering WVC mitigation strategies, the literature review (Appendix A) explored population density control measures, including hunting, lethal management, fertility control, and predator introduction. These methods have contributed to reducing WVCs. However, their effectiveness relies on accurately identifying the locations of animal populations, such as deer. Recalling Section 4.1, the normalized hotspot at Clarksville, TN was 0.645 relating WVCs to TWRA deer hunting records. The corresponding normalized hotspot values for Routes 1, 7, and 15 were 0.067, 0.071, and .165, respectively.

Again, realizing the accuracy concerns of the data, it can only be speculated that population reduction measures would work in these areas.

Other WVC mitigation measures investigated from the literature review were those related to wildlife sensory such as olfaction, auditory, and visual (i.e., reflectors). Only olfactory methods (e.g., odor repellent Pacholek) held some promise (Bíl et al. 2018) where using predator odor was observed less effective at reducing WVCs (Elmeros et al. 2011).

Considering observed incidents between 2019-2023 by month (see Figure 4.6.D(a,g,o)), the number of incidents that occurred during the peak months for Route IDs 1, 7, and 15 were 8 (57.1%), 3 (37.5%), and 6 (46.2%), respectively. Therefore, it is the recommendation of this study that lit/flashing warning signage be used at the entries (both directions) of the 15 WVC routes during the peak months (Grace et al. 2017) – November being a critical month for deer and along some routes in June – and at reduced speeds. Temporary signage that is illuminated or flashing should not lead to human desensitization, as is suggested to occur with permanent signage (Sullivan and Messmer 2003). Additionally, reduced speed (Riginos et al. 2022, Fedorca et al. 2021) may improve reaction time (Pakula et al. 2023), enhancing the ability to avoid collisions.

6.0 Conclusions

In July 2023, the Tennessee Department of Transportation funded this research effort (RES2024-003) to investigate the presence of WVCs across the state and to recommend potential mitigation practices to reduce incidents. Between 2019-2023, there were 37,327 recorded incidents involving animals, the majority being deer (85.1%). The other incidents were simply labeled as “Other Animal” without any other indications of type of animal. An attempt was made to correlate potential deer populations using data from TWRA hunting records over the same time period but inaccuracies in the point coordinates of that data limited its feasibility for use in analyses. Instead, WVCs were linked to TDOT-maintained routes, with 15 routes recording the highest incident counts (ranging from 76 to 131).

Based on an extensive literature review, using fencing to direct animals to a passage that avoids at-grade road crossings can provide the most promising reduction in WVCs. Passages included overpasses, underpasses, and drainage culverts. Complicating the application of fencing along TDOT routes and focusing on the 15 WVC routes was the presence of driveways that fragmented routes beyond standard road intersections. The presence of driveways is expected, and their impact on routes beyond the 15 specified would further complicate the installation of continuous (i.e., unbroken) fencing at effective lengths, as more than three miles is recommended for improved WVC reduction. Of the 15 WVC routes, only three had extended segments exceeding one mile. However, apart from a single underpass, no physical structures were available to prevent animals from entering roadways at the termination of fencing.

Beyond the 15 WVC routes, a lower range of WVCs (58-76 incidents) associated with a TDOT route were randomly investigated to see if driveways posed the same problem for installing uninterrupted fencing at greater distances, preferably at lengths longer than 3 miles. Many TDOT routes in this range were state highways which allow driveway entrances directly from the highway; hence, the presence of numerous driveways observed along these routes prevent the effectiveness of fencing in many areas. There were four interstates that prohibit private entries onto the right-of-way. Two of the interstate segments had underpasses or overpasses that truncated road segments to ineffective lengths. A segment on I-40 held promise for fencing, having an uninterrupted length of approximately seven miles; however, the count of WVCs was 24, which is more than three times less than those recorded on the 15 WVC routes. Another interstate segment (I-24) had two segments, each approximately two miles in length and abutting each other at an underpass with Dixie Bee Rd.

A temporal analysis of the WVCs statewide indicated a heightened number of incidents occurred in November (i.e., deer rutting season) around dusk or dawn. This same pattern of increase WVCs in November was true of the 15 WVC routes; however, a few routes also showed June as an elevated period for incidents. Interestingly, an analysis of the traffic density revealed there was no dependence on the number of WVCs associated with traffic counts.

Upon review of the various WVC mitigation strategies identified from the literature review, it was recommended that flashing signage warning drivers of deer activity and to reduce speed be placed on the 15 WVC routes during November as well as for locations deer activity was shown to also be elevated during June. Using this type of signage rather than installing permanent “deer crossing” placards was believed to avoid desensitization of the warning. As there are many TDOT road segments beyond the 15 analyzed, the detailed analysis of these routes for potential WVC mitigation measures can serve as a model for evaluating other routes of interest.

7.0 References (including those for Appendix A)

Allen, T. D. H., Huijser, M. P., & Willey, D. W. (2013). Effectiveness of wildlife guards at access roads. *Wildlife Society Bulletin, 37*, 402–408.

Alston, J. D., Clark, J. D., Gibbs, D. B., & Hast, J. (2022). Density, harvest rates, and growth of a reintroduced American black bear population. *Journal of Wildlife Management, 86*(1), 1–24.

Ament, R., Huijser, M., & May, D. (2022). *Animal-vehicle collision reduction and habitat connectivity cost-effective solutions - final report* (pp. 1–56).

Ament, R., Wittie, M., & Bell, M. (2021). *Federal lands animal-vehicle collision data coordination project phase 3* (pp. 1–43). Bozeman, MT.

Ascensão, F., Clevenger, A., Santos-Reis, M., Urbano, P., & Jackson, N. (2013). Wildlife-vehicle collision mitigation: Is partial fencing the answer? An agent-based model approach. *Ecological Modelling, 257*, 36–43.

Babińska-Werka, J., Krauze-Gryz, D., Wasilewski, M., & Jasińska, K. (2015). Effectiveness of an acoustic wildlife warning device using natural calls to reduce the risk of train collisions with animals. *Transportation Research Part D: Transport and Environment, 38*, 6–14.

Bashore, T. L., Tzilkowski, W. M., & Bellis, E. D. (1985). Analysis of deer-vehicle collision sites in Pennsylvania. *The Journal of Wildlife Management, 49*, 769–774.

Beasley, J. C., Grazia, T. E., Johns, P. E., & Mayer, J. J. (2013). Habitats associated with vehicle collisions with wild pigs. *Wildlife Research, 40*, 654–660.

Benten, A., Annighöfer, P., & Vor, T. (2018). Wildlife warning reflectors' potential to mitigate wildlife-vehicle collisions: A review on the evaluation methods. *Frontiers in Ecology and Evolution, 6*, 1–12.

Bíl, M., Andrášik, R., Bartonička, T., Křivánková, Z., & Sedoník, J. (2018). An evaluation of odor repellent effectiveness in prevention of wildlife-vehicle collisions. *Journal of Environmental Management, 205*, 209–214.

Bissonette, J. A., & Adair, W. (2008). Restoring habitat permeability to roaded landscapes with isometrically-scaled wildlife crossings. *Biological Conservation, 141*, 482–488.

Bissonette, J. A., Kassar, C. A., & Cook, L. J. (2008). Assessment of costs associated with deer-vehicle collisions: Human death and injury, vehicle damage, and deer loss. *Human–Wildlife Interactions, 2*, 17–27.

Bissonette, J. B., & Kassar, C. A. (2008). Locations of deer-vehicle collisions are unrelated to traffic volume or posted speed limit. *Human–Wildlife Conflicts, 2*, 122–130.

Blackburn, A. M., Heffelfinger, L. J., Veals, A. M., Tewes, M. E., & Young, J. H. (2021). Cats, cars, and crossings: The consequences of road networks for the conservation of an endangered felid. *Global Ecology and Conservation, 27*, e01582.

Blackwell, B. F., & Seamans, T. W. (2009). Enhancing the perceived threat of vehicle approach to deer. *Journal of Wildlife Management, 73*, 128–135.

Blackwell, B. F., Seamans, T. W., & DeVault, T. L. (2014). White-tailed deer response to vehicle approach: Evidence of unclear and present danger. *PLoS ONE, 9*, e109988.

Braunstein, J. L., Clark, J. D., Williamson, R. H., & Stiver, W. H. (2020). Black bear movement and food conditioning in an exurban landscape. *Journal of Wildlife Management, 84*, 1038–1050.

Brennan, L., Chow, E., & Lamb, C. (2022). Wildlife overpass structure size, distribution, effectiveness, and adherence to expert design recommendations. *PeerJ, 10*, 1–19.

Brieger, F., Hagen, R., Vetter, D., Dormann, C. F., & Storch, I. (2016). Effectiveness of light-reflecting devices: A systematic reanalysis of animal-vehicle collision data. *Accident Analysis and Prevention, 97*, 242–260.

Brody, J. A., & Pelton, R. M. (1989). Effects of roads on black bear movements in western North Carolina. *Wildlife Society Bulletin, 17*, 5–10.

Brunen, B., Daguet, C., & Jaeger, J. (2020). What attributes are relevant for drainage culverts to serve as efficient road crossing structures for mammals? *Journal of Environmental Management, 268*, 110423. https://doi.org/10.1016/j.jenvman.2020.110423

Brunen, B., Daguet, C., & Jaeger, J. A. G. (2020). What attributes are relevant for drainage culverts to serve as efficient road crossing structures for mammals? *Journal of Environmental Management, 268*, 110423.

Caldwell, M. R., & Klip, J. M. K. (2020). Wildlife interactions within highway underpasses. *Journal of Wildlife Management, 84*, 227–236.

Chapagain, B. P., & Poudyal, N. C. (2020). Economic benefit of wildlife reintroduction: A case of elk hunting in Tennessee, USA. *Journal of Environmental Management, 269*, 110808. https://doi.org/10.1016/j.jenvman.2020.110808

Chen, H. L., Posthumus, E. E., & Koprowski, J. L. (2021). Potential of small culverts as wildlife passages on forest roads. *Sustainability (Switzerland), 13*, 1–9.

Chen, X., & Wu, S. (2014). Examining patterns of animal-vehicle collisions in Alabama, USA. *Human-Wildlife Interactions, 8*, 235–244.

Ciuffini, F., Tengattini, S., & Bigazzi, A. Y. (2023). Mitigating increased driving after the COVID-19 pandemic: An analysis on mode share, travel demand, and public transport capacity. *Transportation Research Record, 2677*, 154–167.

Clevenger, A. P., & Huijser, M. P. (2011). *Wildlife crossing structure handbook - design and evaluation in North America* (No. FHWA-CFL-TD-11-003).

Clevenger, A. P., & Waltho, N. (2000). Factors influencing the effectiveness of wildlife underpasses in Banff National Park, Alberta, Canada. *Conservation Biology, 14*, 47–56.

Clevenger, A. P., & Waltho, N. (2004). Long-term, year-round monitoring of wildlife crossing structures and the importance of temporal and spatial variability in performance studies. In *Proceedings of the 2003 International Conference on Ecology and Transportation* (pp. 351–365).

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

Clevenger, A. P., Chruszcz, B., & Gunson, K. E. (2001). Highway mitigation fencing reduces wildlife-vehicle collisions. *Wildlife Society Bulletin, 29*, 646–653.

Conard, J. M., & Gipson, P. S. (2006). Spatial and seasonal variation in wildlife-vehicle collisions. *Prairie Naturalist, 38*, 251–260.

Conover, M. R., Pitt, W. C., Kessler, K. K., Dubow, T. J., & Sanborn, A. (1995). Review of human injuries, illnesses, and economic losses caused by wildlife in the United States. *Wildlife Society Bulletin, 23*, 407–414.

Cserkész, T., Ottlecz, B., Cserkész-Nagy, Á., & Farkas, J. (2013). Interchange as the main factor determining wildlife-vehicle collision hotspots on the fenced highways: Spatial analysis and applications. *European Journal of Wildlife Research, 59*, 587–597.

D'Angelo, G.J., D'Angel, J.G., Gallagher, G.R., Osborn, D.A., Miller, K.V., and Warren, R.J. 2006. Evaluation of wildlife warning reflectors for altering white-tailed deer behavior along roadways. Wildlife Society Bulletin 34:1175–1183.

Denicola, A.J., and S.C. Williams. 2008. Sharpshooting suburban white-tailed deer reduces deer–vehicle collisions. Human–Wildlife Conflicts 2:28–33.

DeVault, T.L., T.W. Seamans, and B.F. Blackwell. 2020. Frontal vehicle illumination via rear-facing lighting reduces potential for collisions with white-tailed deer. Ecosphere 11:e03187. 10.1002.

Dodd, N.L., J.W. Gagnon, A.L. Manzo, and R.E. Schweinsburg. 2007. Video surveillance to assess highway underpass use by elk in Arizona. The Journal of Wildlife Management 71:637–645.

Doerr, M.L., J.B. McAninch, and E.P. Wiggers. 2001. Issues urban wildlife comparison of 4 methods to reduce white-tailed deer abundance in an urban community. Wildlife Society Bulletin 29:1105–1113.

Donaldson, B. 2007. Use of highway underpasses by large mammals and other wildlife in Virginia: factors influencing their effectiveness. Transportation Research Record 157–164.

Donaldson, B.M., and M.H. Schaus. 2010. An evaluation of the U.S. highway 17 underpass in Chesapeake, Virginia, as a wildlife crossing. Vol. 17. Charlottesville, VA. 1–16 pp.

Donaldson, B.M., and Y.J. Kweon. 2019. Effectiveness of seasonal deer advisories on changeable message signs as a deer crash mitigation tool. Transportation Research Record. Vol. 2673. Charlottesville, VA. 548–557 pp.

Donaldson, B.M., Y.J. Kweon, and L.N. Lloyd. 2016. Roadside activity and behavior of white-tailed deer and other wildlife near unfenced underpasses. Transportation Research Record 2571:29–38.

Druta, C., and A.S. Alden. 2020. Preventing animal-vehicle crashes using a smart detection technology and warning system. Transportation Research Record 2674:680–689.

Edwards, H.A., E. Lebeuf-Taylor, M. Busana, and J. Paczkowski. 2022. Road mitigation structures reduce the number of reported wildlife-vehicle collisions in the Bow Valley, Alberta, Canada. Conservation Science and Practice e12778.

Elmeros, M., J.K. Winbladh, P.N. Andersen, A.B. Madsen, and J.T. Christensen. 2011. Effectiveness of odour repellents on red deer (Cervus elaphus) and roe deer (Capreolus capreolus): a field test. European Journal of Wildlife Research 57:1223–1226.

Eslinger, R., and J.D. Morgan. 2017. Spatial cluster analysis of high-density vehicle–bear collisions and bridge locations. Papers in Applied Geography 3:171–181. Taylor & Francis.

Farrell, M. C., & Tappe, P. A. (2007). County-level factors contributing to deer-vehicle collisions in Arkansas. *The Journal of Wildlife Management, 71*, 2727–2731.

Fedorca, A., Fedorca, M., Ionescu, O., Jurj, R., Ionescu, G., & Popa, M. (2021). Sustainable landscape planning to mitigate wildlife–vehicle collisions. *Land, 10*, 737.

Finder, R. A., Roseberry, J. L., & Woolf, A. (1999). Site and landscape conditions at white-tailed deer/vehicle collision locations in Illinois. *Landscape and Urban Planning, 44*, 77–85.

Ford, A. T., & Clevenger, A. P. (2010). Validity of the prey-trap hypothesis for carnivore-ungulate interactions at wildlife-crossing structures. *Conservation Biology, 24*, 1679–1685.

Ford, A. T., Barrueto, M., & Clevenger, A. P. (2017). Road mitigation is a demographic filter for grizzly bears. *Wildlife Society Bulletin, 41*, 712–719.

Ford, A. T., Dorsey, B., Lee, T. S., & Clevenger, A. P. (2022). A before-after-control-impact study of wildlife fencing along a highway in the Canadian Rocky Mountains. *Frontiers in Conservation Science, 3*, 1–11.

Foster, M. L., & Humphrey, S. R. (1995). Use of highway underpasses by Florida panthers and other wildlife. *Wildlife Society Bulletin, 23*, 95–100.

Gagnon, J. W., Loberger, C. D., Ogren, K. S., Sprague, S. C., Boe, S. R., & Schweinsburg, R. E. (2022). Mitigating bighorn sheep–vehicle collisions and habitat fragmentation with overpasses and adaptive mitigation. *Human-Wildlife Interactions, 16*, 353–372.

Gagnon, J. W., Loberger, C. D., Sprague, S. C., Ogren, K. S., Boe, S. L., & Schweinsburg, R. E. (2015). Cost-effective approach to reducing collisions with elk by fencing between existing highway structures. *Human-Wildlife Interactions, 9*, 248–264.

Gilbert, S. L., Sivy, K. J., Pozzanghera, C. B., DuBour, A., Overduijn, K., Smith, M. M., Zhou, J., Little, J. M., & Prugh, L. R. (2017). Socioeconomic benefits of large carnivore recolonization through reduced wildlife-vehicle collisions. *Conservation Letters, 10*, 430–438.

Gkritza, K., Baird, M., & Hans, Z. N. (2010). Deer-vehicle collisions, deer density, and land use in Iowa's urban deer herd management zones. *Accident Analysis and Prevention, 42*, 1916–1925.

Goosem, M., Weston, N., & Bushnell, S. (2005). Effectiveness of rope bridge arboreal overpasses and faunal underpasses in providing connectivity for rainforest fauna. In *Proceedings of the International Conference on Ecology and Transportation* (pp. 304–316).

Gordon, K. M., & Anderson, S. H. (2003). Mule deer use of underpasses in western and southeastern Wyoming. In *ICOET 2003 Proceedings* (pp. 309–318).

Grace, M. K., Smith, D. J., & Noss, R. F. (2017). Reducing the threat of wildlife-vehicle collisions during peak tourism periods using a Roadside Animal Detection System. *Accident Analysis and Prevention, 109*, 55–61.

Gulia-Nuss, M., Nuss, A. B., Meyer, J. M., Sonenshine, D. E., Roe, R. M., Waterhouse, R. M., Sattelle, D. B., De La Fuente, J., Ribeiro, J. M., Megy, K., Thimmapuram, J., Miller, J. R., Walenz, B. P., Koren, S., Hostetler, J. B., Thiagarajan, M., Joardar, V. S., Hannick, L. I., Bidwell, S., ... Hill, C. A. (2016). Genomic insights into the *Ixodes scapularis* tick vector of Lyme disease. *Nature Communications, 7*, 10507.

Gulsby, W. D., Stull, D. W., Gallagher, G. R., Osborn, D. A., Warren, R. J., Miller, K. V., & Tannenbaum, L. V. (2011). Movements and home ranges of white-tailed deer in response to roadside fences. *Wildlife Society Bulletin, 35*, 282–290.

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

Ha, H., & Shilling, F. (2018). Modelling potential wildlife-vehicle collision (WVC) locations using environmental factors and human population density: A case study from three state highways in central California. *Ecological Informatics, 43*, 212–221. Elsevier.

Hanberry, B. B., & Hanberry, P. (2020). Regaining the history of deer populations and densities in the southeastern United States. *Wildlife Society Bulletin, 44*, 512–518.

Hardy, A., Clevenger, A. P., Huijser, M. P., & Neale, G. (2003). An overview of methods and approaches for evaluating the effectiveness of wildlife crossing structures: Emphasizing the science in applied science. *Proceedings of the 2003 International Conference on Ecology and Transportation*, 319–330.

Harper, C. A. (2002). Using single-strand fencing to manage deer damage. *University of Tennessee SP598.*

Hooker, M. J., Osborn, D. A., Chamberlain, M. J., Warren, R. J., Miller, K. V., University of Georgia, Georgia Department of Transportation, & Federal Highway Administration. (2016). *Efficacy of road underpasses for minimizing bear-vehicle collisions on the four-lane section of Georgia Highway 96 – Phase I* (p. 54).

Hou, N. (2022, May). Research on measures and improvement of fragmented ecological protection in road construction. In *2022 International Conference on Urban Planning and Regional Economy (UPRE 2022)* (pp. 256–260). Atlantis Press.

Huijser, M. P., Duffield, J. W., Clevenger, A. P., Ament, R. J., & McGowen, P. T. (2009). Cost-benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada: A decision support tool. *Ecology and Society, 14*.

Huijser, M. P., Fairbank, E. R., Camel-Means, W., Graham, J., Watson, V., Basting, P., & Becker, D. (2016). Effectiveness of short sections of wildlife fencing and crossing structures along highways in reducing wildlife-vehicle collisions and providing safe crossing opportunities for large mammals. *Biological Conservation, 197*, 61–68.

Huijser, M. P., Kociolek, A. V., Allen, T. D. H., & American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on the Environment. (2015). *Construction guidelines for wildlife fencing and associated escape and lateral access control measures* (p. 218).

Huijser, M. P., Wagner, M. E., Hardy, A., Clevenger, A. P., & Fuller, J. A. (2007). Animal-vehicle collision data collection throughout the United States and Canada. In *ICOET 2007 Proceedings* (pp. 387–391).

Huijser, M., McGowen, P., Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., & Ament, R. (2008). *Wildlife-vehicle collision reduction study: Report to Congress* (pp. 1–254).

Hurley, M. V., Rapaport, E. K., & Johnson, C. J. (2009). Utility of expert-based knowledge for predicting wildlife-vehicle collisions. *The Journal of Wildlife Management, 73*, 278–286.

Jensen, A. J., Perrine, J. D., Schaffner, A. A., Brewster, R. A., Giordano, A. J., Robertson, M., & Siepel, N. R. (2022). Quantifying wildlife use of escape ramps along a fenced highway. *Human-Wildlife Interactions, 16*, 133–143.

Jensen, A. J., Perrine, J. D., Siepel, N., & Robertson, M. (2018). A proposed analysis of deer use of jumpout ramps and wildlife use of culverts along a highway with wildlife exclusion fencing. *Proceedings of the Vertebrate Pest Conference, 28*, 145–151.

Jones, E. R., Lancia, R., & Doerr, P. (2008). *The effectiveness of wildlife crossing structures for black bears in Madison County, North Carolina* (p. 1–123). Raleigh, North Carolina.

Kilgo, J. C., Blake, J. I., Grazia, T. E., Horcher, A., Larsen, M., Mims, T., & Zarnoch, S. J. (2020). Use of roadside deer removal to reduce deer-vehicle collisions. *Human-Wildlife Interactions, 14*, 87–95.

Kindall, J. L., Muller, L. I., Clark, J. D., Lupardus, J. L., & Murrow, J. L. (2011). Population viability analysis to identify management priorities for reintroduced elk in the Cumberland Mountains, Tennessee. *The Journal of Wildlife Management, 75*, 1745–1752.

Kurth, K. A., Watson, E. M., Gerhold, R. W., Metts, D. L., Miller, B. F., Morin, D. J., Eda, S., Yang, S. I., & Muller, L. I. (2023). Mortality, survival, and serologic results for elk (*Cervus canadensis*) in the Cumberland Mountains of Tennessee, USA. *Journal of Wildlife Diseases, 59*, 420–431.

Kusak, J., Huber, D., Gomerčić, T., Schwaderer, G., & Gužvica, G. (2009). The permeability of a highway in Gorski Kotar (Croatia) for large mammals. *European Journal of Wildlife Research, 55*, 7–21.

Lee, T. S., Rondeau, K., Schaufele, R., Clevenger, A. P., & Duke, D. (2021). Developing a correction factor to apply to animal-vehicle collision data for improved road mitigation measures. *Wildlife Research, 48*, 501–510.

Litvaitis, J. A., & Tash, J. P. (2008). An approach toward understanding wildlife-vehicle collisions. *Environmental Management, 42*, 688–697.

Lob, D. L., & M. (2001). Wildlife crossing designs and use by Florida panthers and other wildlife. *Florida Fish and Wildlife*, Naples, Florida, 1–7.

Massei, G. (2023). Fertility control for wildlife: A European perspective. *Animals, 13*, 45.

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

McCollister, M. F., & Van Manen, F. T. (2010). Effectiveness of wildlife underpasses and fencing to reduce wildlife-vehicle collisions. *The Journal of Wildlife Management, 74*, 1722–1731.

McGuire, T. M., & Morrall, J. F. (2000). Strategic highway improvements to minimize environmental impacts within the Canadian Rocky Mountain National Parks. *Journal of Allergy and Clinical Immunology, 27*, 523–532.

McGuire, T. M., Clevenger, A. P., Ament, R., Callahan, R., Jacobson, S., & B. M. (2021). *Innovative strategies to reduce the costs of effective wildlife overpasses* (p. 44).

Miller, L. A., Fagerstone, K. A., & Eckery, D. C. (2013). Twenty years of immunocontraceptive research: Lessons learned. *Journal of Zoo and Wildlife Medicine, 44*, S84–S96.

Mountrakis, G., & Gunson, K. (2009). Multi-scale spatiotemporal analyses of moose-vehicle collisions: A case study in northern Vermont. *International Journal of Geographical Information Science, 23*, 1389–1412.

Muller, L. I., Hackworth, A. M., Giffen, N. R., Evans, J. W., Henning, J., Hickling, G. J., & Allen, P. (2014). Spatial and temporal relationships between deer harvest and deer-vehicle collisions at Oak Ridge Reservation, Tennessee. *Wildlife Society Bulletin, 38*, 812–820.

Ng, S. J., Dole, J. W., Sauvajot, R. M., Riley, S. P. D., & Valone, T. J. (2004). Use of highway undercrossings by wildlife in southern California. *Biological Conservation, 115*, 499–507.

Nojoumi, M., Clevenger, A. P., Blumstein, D. T., & Abelson, E. S. (2022). Vehicular traffic effects on elk and white-tailed deer behavior near wildlife underpasses. *PLoS ONE, 17*, 1–10.

O'Bryan, C. J., Braczkowski, A. R., Beyer, H. L., Carter, N. H., Watson, J. E. M., & McDonald-Madden, E. (2018). The contribution of predators and scavengers to human well-being. *Nature Ecology and Evolution, 2*, 229–236.

Olson, D. D., Bissonette, J. A., Cramer, P. C., Green, A. D., Davis, S. T., Jackson, P. J., & Coster, D. C. (2014). Monitoring wildlife-vehicle collisions in the information age: How smartphones can improve data collection. *PLoS ONE, 9*, e98613.

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

Pakula, C. J., Guenin, S., Skaggs, J., Rhodes, O. E., & DeVault, T. L. (2023). Driving in the dark: Deciphering nighttime driver detection of free-ranging roadside wildlife. *Transportation Research Part D: Transport and Environment, 122*, 103873.

Parkhurst, B. C. W. (2002). Interactions between deer damage, deer density, and stakeholder attitudes in Virginia. *Wildlife Society Bulletin, 30*, 139–147.

Puglisi, M. J., Lindzey, J. S., & Bellis, E. D. (1974). Factors associated with highway mortality of white-tailed deer. *The Journal of Wildlife Management, 38*, 799–807.

Raynor, J. L., Grainger, C. A., & Parker, D. P. (2021). Wolves make roadways safer, generating large economic returns to predator conservation. *Proceedings of the National Academy of Sciences of the United States of America, 118*, 1–10.

Resop, L., Demarais, S., Strickland, B. K., McKinley, W. T., & Street, G. (2024). Rutting and rambling: Movement characteristics reveal partial migration in adult male white-tailed deer at a latitude void of chronic and severe environmental fluctuations. *Ecology and Evolution, 14*, 1–12.

Reynolds-Hogland, M. J., & Mitchell, M. S. (2007). Effects of roads on habitat quality for bears in the southern Appalachians: A long-term study. *Journal of Mammalogy, 88*, 1050–1061.

Riginos, C., Fairbank, E., Hansen, E., Kolek, J., & Huijser, M. P. (2022). Reduced speed limit is ineffective for mitigating the effects of roads on ungulates. *Conservation Science and Practice, 4*, 1–13.

Romin, L. A., & Bissonette, J. A. (1996). Deer-vehicle collisions: Status of state monitoring activities and mitigation efforts. *Wildlife Society Bulletin, 24*, 276–283.

Romin, L. A., & Dalton, L. B. (1992). Lack of response by mule deer to wildlife warning whistles. *Wildlife Society Bulletin, 20*, 382–384.

Rutberg, A. T., & Naugle, R. E. (2008). Deer-vehicle collision trends at a suburban immunocontraception site. *Human-Wildlife Conflicts, 2*, 60–67.

Saint-Andrieux, C., Calenge, C., & Bonenfant, C. (2020). Comparison of environmental, biological and anthropogenic causes of wildlife–vehicle collisions among three large herbivore species. *Population Ecology, 62*, 64–79.

Santos, R. A. L., Santos, S. M., Santos-Reis, M., De Figueiredo, A. P., Bager, A., Aguiar, L. M. S., & Ascensão, F. (2016). Carcass persistence and detectability: Reducing the uncertainty surrounding wildlife-vehicle collision surveys. *PLoS ONE, 11*, 1–15.

Santos, S. M., Carvalho, F., & Mira, A. (2011). How long do the dead survive on the road? Carcass persistence probability and implications for road-kill monitoring surveys. *PLoS ONE, 6*.

Sawaya, M. A., Clevenger, A. P., & Schwartz, M. K. (2019). Demographic fragmentation of a protected wolverine population bisected by a major transportation corridor. *Biological Conservation, 236*, 616–625. Elsevier.

Sawaya, M. A., Kalinowski, S. T., & Clevenger, A. P. (2014). Genetic connectivity for two bear species at wildlife crossing structures in Banff National Park. *Proceedings of the Royal Society B: Biological Sciences, 281*.

Sawyer, H., Rodgers, P. A., & Hart, T. (2016). Pronghorn and mule deer use of underpasses and overpasses along U.S. Highway 191. *Wildlife Society Bulletin, 40*, 211–216.

Schmidt, G. M., Lewison, R. L., & Swarts, H. M. (2021). Pairing long-term population monitoring and wildlife crossing structure interaction data to evaluate road mitigation effectiveness. *Biological Conservation, 257*, 109085. Elsevier Ltd.

Schwabe, K. A., Schuhmann, P. W., & Tonkovich, M. (2002). A dynamic exercise in reducing deer-vehicle collisions: Management through vehicle mitigation techniques and hunting. *Journal of Agricultural and Resource Economics, 27*, 261–280.

Sèbe, M., Briton, F., & Kinds, A. (2023). Does predation by wolves reduce collisions between ungulates and vehicles in France? *Human Dimensions of Wildlife, 28*, 281–293. Routledge.

Shilling, F. M., & Waetjen, D. P. (2015). Wildlife-vehicle collision hotspots at US highway extents: Scale and data source effects. *Nature Conservation, 11*, 41–60.

Shilling, F., Collinson, W., Bil, M., Vercayie, D., Heigl, F., Perkins, S. E., & MacDougall, S. (2020). Designing wildlife-vehicle conflict observation systems to inform ecology and transportation studies. *Biological Conservation, 251*, 108797. Elsevier.

Sijtsma, F. J., van der Veen, E., van Hinsberg, A., Pouwels, R., Bekker, R., van Dijk, R. E., Grutters, M., Klaassen, R., Krijn, M., Mouissie, M., & Wymenga, E. (2020). Ecological impact and cost-effectiveness of wildlife crossings in a highly fragmented landscape: A multi-method approach. *Landscape Ecology, 35*, 1701–1720.

Simpson, N. O., Stewart, K. M., Schroeder, C., Cox, M., Huebner, K., & Wasley, T. (2016). Overpasses and underpasses: Effectiveness of crossing structures for migratory ungulates. *Journal of Wildlife Management, 80*, 1370–1378.

Slater, F. M. (2002). An assessment of wildlife road casualties – the potential. *Web Ecology*, 33–42.

Snow, N. P., Porter, W. F., & Williams, D. M. (2015). Underreporting of wildlife-vehicle collisions does not hinder predictive models for large ungulates. *Biological Conservation, 181*, 44–53. Elsevier Ltd.

Sorensen, A., van Beest, F. M., & Brook, R. K. (2014). Impacts of wildlife baiting and supplemental feeding on infectious disease transmission risk: A synthesis of knowledge. *Preventive Veterinary Medicine, 113*, 356–363. Elsevier B.V.

Sparks, J. L., & Gates, J. E. (2012). An investigation into the use of road drainage structures by wildlife in Maryland, USA. *Human-Wildlife Interactions, 6*, 311–326.

Stickles, J. H., Cohen, B. S., Osborn, D. A., Warren, R. J., D'Angelo, G. J., & Miller, K. V. (2022). Nighttime traffic volume predicts risk of deer–vehicle collisions. *Human-Wildlife Interactions, 16*, 44–52.

Stratman, M. R., Alden, C. D., Pelton, M. R., & Sunquist, M. E. (2001). Long distance movement of a Florida black bear in the Southeastern Coastal Plain. *International Association for Bear Research and Management, 12*, 55–58.

Sugiarto, W. (2023). Impact of wildlife crossing structures on wildlife–vehicle collisions. *Transportation Research Record, 2677*, 670–685.

Sullivan, J. M. (2011). Trends and characteristics of animal-vehicle collisions in the United States. *Journal of Safety Research, 42*, 9–16. Elsevier Ltd.

Sullivan, T. L., & Messmer, T. A. (2003). Perceptions of deer-vehicle collision management by state wildlife agency and department of transportation administrators. *Wildlife Society Bulletin, 31*, 163–173.

Teixeira, F. Z., Coelho, A. V. P., Esperandio, I. B., & Kindel, A. (2013). Vertebrate road mortality estimates: Effects of sampling methods and carcass removal. *Biological Conservation, 157*, 317–323. Elsevier Ltd.

Tennessee Department of Safety and Homeland Security. (2020). *2020 Crash facts - Deer*. Available online at https://www.tn.gov/content/dam/tn/safety/documents/crash_stats/crash_facts/2020_Crash_Facts_Deer.pdf

Tennessee Wildlife Resources Agency (TWRA). (2005). *White-tail Deer Odocoileus virginianus*. Available online at https://www.tn.gov/twra/wildlife/mammals/large/deer.html

Tennessee Wildlife Resources Agency (TWRA). (2020). *Elk in Tennessee*. Retrieved from https://www.tn.gov/twra/wildlife/mammals/large/elk.html

Tiedeman, K., Hijmans, R. J., Mandel, A., Waetjen, D. P., & Shilling, F. (2019). The quality and contribution of volunteer collected animal vehicle collision data in ecological research. *Ecological Indicators, 106*, 105431. Elsevier.

Transportation, T. D. of. (2015). *TDOT 25-year long-range transportation policy plan - potential environmental mitigation strategies*. 1–18 pp.

Trombulak, S. C., & Frissell, C. A. (2000). Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology, 14*, 18–30.

TWRA. (2023). *Black bears in Tennessee*. Available online at https://www.tn.gov/twra/wildlife/mammals/large/black-bears.html

U.S. Department of Agriculture (USDA). (2024). *Terrestrial wildlife crossing structure types (by function)*. Retrieved March 2024, from https://www.fs.usda.gov/wildlifecrossings/glossary/documents/WildlifeCrossingStructureTypesByFunctionIAWHI.pdf

United States Department of Agriculture, Forest Service (USDA-FS), P. S. R. S. (2021). Highway crossing structures for wildlife: Opportunities for improving driver and animal safety. M. Ament, R., Jacobson, S., Callahan, R., & Brocki (Eds.). Albany, CA. 1–51 pp.

University of Tennessee. (2024). *SNR faculty collaborate with TWRA, others on elk reproduction study*. Available online at https://naturalresources.tennessee.edu/snr-faculty-collaborate-with-twra-others-on-elk-reproduction-study/

Valerio, F., Basile, M., & Balestrieri, R. (2021). The identification of wildlife-vehicle collision hotspots: Citizen science reveals spatial and temporal patterns. *Ecological Processes, 10*.

Valitzski, S. A., D'Angelo, G. J., Gallagher, G. R., Osborn, D. A., Miller, K. V., & Warren, R. J. (2009). Deer responses to sounds from a vehicle-mounted sound-production system. *The Journal of Wildlife Management, 73*, 1072–1076.

Van Manen, F. T., McCollister, M. F., Nicholson, J. M., Thompson, L. M., Kindall, J. L., & Jones, M. D. (2012). Short-term impacts of a four-lane highway on American black bears in eastern North Carolina. *Wildlife Monographs*, 1–35.

Van, S. E., & Worm, P. B. (2001). The use of a motorway wildlife overpass by large mammals. *Netherlands Journal of Zoology, 51*, 97–105.

Vance, J. A., Smith, W. H., & Smith, G. L. (2018). Species composition and temporal patterns of wildlife-vehicle collisions in southwest Virginia, USA. *Human-Wildlife Interactions, 12*, 417–426.

VerCauteren, K. C., Seward, N. W., Lavelle, M. J., Fischer, J. W., & Phillips, G. E. (2009). Deer guards and bump gates for excluding white-tailed deer from fenced resources. *National Wildlife, 3*, 145–153.

Waring, G. H., Griffis, J. L., & Vaughn, M. E. (1991). White-tailed deer roadside behavior, wildlife warning reflectors, and highway mortality. *Applied Animal Behaviour Science, 29*, 215–223.

Wilkins, D. C., Kockelman, K. M., & Jiang, N. (2019). Animal-vehicle collisions in Texas: How to protect travelers and animals on roadways. *Accident Analysis and Prevention, 131*, 157–170.

Williams, A. F., & Wells, J. K. (2005). Characteristics of vehicle-animal crashes in which vehicle occupants are killed. *Traffic Injury Prevention, 6*, 56–59.

Wood, P., & Wolfe, M. L. (1988). Intercept feeding as a means of reducing deer-vehicle collisions. *Wildlife Society Bulletin, 16*, 376–380.

Appendix A

Wildlife-vehicle Collision Mitigation Strategies for the Tennessee Department of Transportation (TDOT): A Review

Authored by: R. A. Butler, T. L. DeVault, and G. J. D'Angelo

Literature Review Summary – University of Georgia

Mitigating wildlife-vehicle collisions (WVCs) remains a complex ecological and socioeconomic issue which is exacerbated by expanding road networks and wildlife populations in the United States (US). In Tennessee, human-wildlife interactions on roadways are increased by substantially growing white-tailed deer (Odocoileus virginianus) and human population densities, reintroductions of wildlife species, and no universally accepted method for WVC mitigation. Here, with a focus on WVC mitigation strategies and/or structures which could be useful for the Tennessee Department of Transportation (TDOT), a robust review of available information is presented. Specifically, four main objectives were identified to be addressed which included 1) conducting a robust literature review on topics for best practices in determining WVCs from various data sources, 2) identifying methods for estimating unaccounted-for WVCs, 3) identifying transportation route and environmental characteristics that correlate with WVCs, and 4) identifying mitigation practices that reduce WVCs effectively and inexpensively. Overall, 159 studies were reviewed from databases including Science Direct, JSTOR, Springer Link, and Google Scholar which included methods for reducing WVCs.

The greatest challenge to reducing WVCs is improving data collection and management because decisions for when and where to implement mitigation strategies are reliant on available and accurate data. Methods used to improve carcass count accuracy, the inclusion of citizen science, video and camera surveillance, and workshops could all be used to more effectively record the number of WVCs in Tennessee. Methods for decreasing unaccounted for WVCs may include the use of frequent carcass counts and correction factors, whereas the use of mobile devices and citizen science can increase spatial data accuracy by incorporating GPS and enhanced reporting. Additionally, agency and stakeholder collaboration are important for enhancing data quality and validation.

Targeting hotspots where WVCs frequently occur along roadsides is beneficial for sighting and identifying potential reduction strategies, but this information can be used to reduce wildlife-vehicle interactions as well. For example, in some WVC hotspot areas, managing vegetation along roadsides can shift wildlife habitats ultimately affecting WVCs. Additionally, nonstructural or nonenvironmental hot spots can be used to reduce or identify WVCs, such as increased lighting to enhance visibility, reduced speed limits to increase detection, and avoidance time.

There are also methods which increase driver awareness to reduce WVCs; these include the use of signage or driver detection systems. Some methods proposed to reduce WVCs focus on wildlife population density control. For example, the use of fertility control, culling, or predator introduction can be used to reduce wildlife populations which ultimately decrease their potential for interactions with vehicles. Techniques focused on wildlife sensory systems, such as olfaction, auditory, or visual, have been introduced to deter wildlife away from roadways, although these methods are not as effective at reducing WVCs as others. Additionally, mitigation structure implementation, in the form of fencing, underpasses, overpasses, and culverts, has proven to be a reliable method for reducing WVCs. Considerations for wildlife species interactions and habituation near areas where WVC reduction methods are implemented is vital for ensuring the mitigation measures are effective and if structural measures are employed that animals are effectively using them.

Tailoring WVC implementation tactics to target species preferences is key to reducing wildlife-vehicle interactions. The use of multiple structure types is the most effective method at reducing WVCs because this targets a variety of species. For example, fencing in combination with overpasses can funnel wildlife away from roads and onto mitigation structures. Environmental components, such as waterways and/ or vegetation, should also be considered when implementing WVC mitigation strategies because these factors can often attract or repel wildlife from an area and can be species-specific. For example, increased mitigation structure distance to a drainage area has been found to increase black bear use of a crossing structure. An additional challenge for reducing WVCs are the immense costs associated with structure construction and maintenance. Choosing structures that specifically target an area and species and in which the benefits outweigh costs are important in considerations. For example, fencing has been shown to be of lower cost compared to overpasses and is an effective method for deterring wildlife away from roadways. Overall, effectively decreasing WVCs in Tennessee will require a multi-faceted approach including agency collaboration and corporation to enhance data retrieval to then inform decisions on where, when, and what mitigation methods should be chosen for species-specific WVC reductions.

Introduction

Wildlife-vehicle collisions (WVCs) present an increasing problem in North America (Huijser et al. 2009). In the U.S. alone, it is estimated that there are 1-2 million WVCs per year with annual costs up to $8.4 Billion (Conover et al. 1995; Huijser et al. 2008). Increases in the number of roadways and highway miles have led to a growing number of WVCs with rising socioeconomic consequences such as driver safety and health (Sullivan and Messmer 2003; Bissonette et al. 2008). Collisions with large mammal species can result in considerable property damage or even human fatalities (Wells 2005; Bissonette et al. 2008; Huijser et al. 2008). Although collisions with smaller-sized wildlife are a frequent occurrence, large mammal-vehicle collisions (e.g., bear, moose, etc.) pose a greater concern due to their ability to cause significant injury or property damage (Wells 2005; Litvaitis and Tash 2008; Ha and Shilling 2018). It is estimated that there is one human death for every 3,441 deer (Odocoileus spp.)-vehicle collisions (Conover et al. 1995). Although only 4-10% of WVCs cause motorist injury, nearly 100% of WVCs with large wildlife species (e.g., bear, moose, etc.) result in considerable property damage (Huijser et al 2008). Additionally, damages caused by WVCs economic impacts by increasing insurance premiums (Hurley et al. 2009).

Wildlife crossing structures across roadways are mechanisms which can be used to reduce WVCs and decrease the likelihood of property damage or serious human injury (USDA-FS 2021). Wildlife-vehicle mitigation structures allow wildlife to cross under or over roads, often including the use of fencing to guide animals, to reduce WVCs by providing safe passageways for crossing (USDA-FS 2021). Initial installation and maintenance of WVC mitigation structures can be expensive; however, the cost-benefit ratio for their implementation, 3.0 for underpass and underpasses and 30 for wildlife fencing, outweighs all disadvantages (Wilkins et al. 2019). Mitigation structures increase benefit-cost ratios by decreasing vehicle collisions and their associated economic impacts, improving human safety on roadways, and increasing habitat connectivity (Bissonette and Adair 2008; Huijser et al. 2016). For example, in one case, an 80% reduction in large mammal WVC was achieved on long roadway lengths by implementing mitigation measures (Huijser et al. 2016).

As another consideration, roadways pose a serious ecological risk to wildlife by fragmenting ecosystems, resulting in negative genetic consequences (Sullivan and

Messmer 2003; Sawaya et al. 2014; Sawaya et al. 2019; Edwards et al. 2022) and the survivability of wildlife populations is threatened by WVCs (Trombulak and Frissell 2000; Huijser et al. 2008). Roadways are also a concern for threatened or endangered species, and roadways can have catastrophic impacts on population densities of critical species (Blackburn et al. 2021). Therefore, it is imperative that future transportation construction decisions be made to incorporate habitat fluidity as road networks increase to accommodate a growing population (Sawaya et al. 2019). Wildlife crossing structures can reduce habitat fragmentation by connecting environments which would have otherwise been disconnected by roadways (Foster 1995).

Due to the considerable costs of wildlife collision mitigation strategies (> $1 million in some cases), it is imperative that implementation of WVC mitigation techniques incorporate species preferences, or they are likely to fail (Litvaitis and Tash 2008; Wilkins et al. 2019; Brennan et al. 2022). Knowing landscape characteristics associated with road mortalities for a particular wildlife species of interest can be important for WVC mitigation (Conard and Gipson 2006). Wildlife species vary in abundances and movement patterns throughout landscapes and these factors are associated with different collision densities (Saint-Andrieux et al. 2020). Management of focal species should incorporate strategies which target locations where species' preferred habitats intersect roadways and where WVCs are spatially clustered (Beasley et al. 2013). Wildlife-vehicle collisions are non-randomly aggregated along roadways (Eslinger and Morgan 2017; Cserkész et al. 2013) and there is a vital need for incorporating environmental and biological factors associated with WVCs (Saint-Andrieux et al. 2020).

Many agencies do not have designated personnel with job responsibilities directed at reducing WVCs and lack sufficient data for the purpose of documenting animal collisions (Sullivan and Messmer 2003). Agencies which report WVCs are often inconsistent in data reporting, which is alarming because quality data are important for accurately assessing WVC mitigation implementation and hotspot alterations over time (Huijser et al. 2007). Additionally, most WVCs go unreported, which may stem from drivers' attempts to avoid future insurance cost increases and can distort model results (Wilkins et al. 2019). Underreporting can skew the relationship between environmental factors and WVCs, obscuring the relationships between the variables (Snow et al. 2015). Models have some ability to predict WVC hotspots using underreported data; however, these models have less predictive power when underreporting is greater than 70% or in addition to spatial bias (Snow et al. 2015).

Wilkins et al. (2019) noted the effects from underreporting can create extreme biases in the estimation of WVCs.

Vehicle collisions associated with wildlife are a problem in Tennessee along with the need to protect critical species of ecological and economic concern (Braunstein et al. 2020; Chapagain and Poudyal 2020; Tennessee Department of Safety and Homeland Security 2020). Mitigation strategies for WVCs are included in Tennessee Department of Transportation's (TDOT's) 25-year Plan which also aims to incorporate methods of habitat restoration (Transportation 2015). Therefore, herein we provide a systematic review of the existing literature to further understand factors associated with WVCs and methods for their control which are appropriate for Tennessee roads, habitats, and animal species. We also created a selection matrix based on data from other states that have similar environmental and roadway characteristics and wildlife species to Tennessee. The selection matrix considers effectiveness, design, average cost, and timing. This study addresses four main objectives which included 1) conducting a robust literature review on topics for best practices in determining WVCs from various data sources, 2) identifying methods for estimating unaccounted-for WVCs, 3) identifying transportation route and environmental characteristics that correlate with WVCs, and 4) recommending mitigation practices that reduce WVCs effectively and inexpensively.

Methods

We completed a systemic review for wildlife collision mitigation techniques and structures that could be implemented by TDOT to reduce WVCs. Scientific literature was examined using online databases Science Direct (https://www.sciencedirect.com), JSTOR (https://www.jstor.org), Springer Link (https://link.springer.com), and Google Scholar (https://scholar.google.com). We researched literature during the period of December 2023-May 2024 and included relevant topics associated with WVCs which included the years 1974-2024. Literature was considered for inclusion based on the relevance for habitat, geographical locations, or species similarities to those found in the state of Tennessee. We focused our attention on wildlife species which are responsible for the majority of WVCs, species which could cause significant property damage, or species of economic concern in Tennessee. Species of concern for mitigating WVCs in Tennessee included keywords "deer", "ungulate", "elk", "pig", "boar", "black bear", "coyote", or "bear". To find methods for reducing WVCs, searches included the keywords "wildlife-vehicle collision", "wildlife-vehicle collision hotspot", "wildlife habituate crossing structure", “human related wildlife-vehicle collision”, “wildlife crossing structure”, or “wildlife passage”. We searched available literature for identification of environmental and human-related factors which could relate to WVC hotspots and methods to be used for habituating wildlife to mitigate structures for improving animal use. To do this, we used key words “wildlife-vehicle collision hotspot”, “wildlife habituate crossing structure”, and “human related wildlife-vehicle collision”. To search for literature pertaining to unreported WVCs keywords “unreported wildlife-vehicle collision” and “under reported wildlife-vehicle collision” were used. Key word searches were also conducted in the cited literature for papers that were found from direct searches. Three separate matrix tables were made by incorporating mitigation strategies for unaccounted-for wildlife-vehicle collisions, characteristics associated with wildlife-vehicle collisions, and mitigation practices from research papers with similar keywords (see tables at end of this appendix). Mitigation strategies and hot spots, which could be appropriately used to reduce WVCs from research papers, were considered and incorporated into each suitable matrix table. Finally, information from each matrix table was extracted to incorporate into the recommendations section.

Results

Overall, 159 studies or reports were reviewed which focused on mitigation strategies for ungulates and large carnivores and also incorporated small and medium mammals. Twenty-one studies which proposed methods to improve data collection and reduce the number of unreported WVCs were included (Table AP1). A total of 65 studies were focused on key conditions that contribute to WVCs. Of those, 29 focused on environmental factors, nine focused on structural factors, and 27 considered nonstructural methods (Table AP2). Eighty studies were used to identify methods for reducing WVCs. Fifty-two studies were reviewed that were associated with structural methods for reducing WVCs, 18 for population control, and 19 nonstructural methods (Table AP3).

Discussion

Wildlife species of concern in Tennessee

Tennessee provides a diverse habitat for many species. Due to the focus on wildlife vehicle interactions and the intent to improve driver safety, this report is primarily focused on large animals that would cause significant impacts to human lives and property. For Tennessee, the predominant species of concern are black bear, elk, and white-tailed deer.

Intense 20th century collaborative management efforts in Tennessee have drastically increased black bear populations with a reported 1.2 mean annual growth rate (Alston et al. 2022; TWRA 2023). It is understood that increases in bear populations will result in increased activity patterns outside of protected areas, resulting in heightened roadway fatalities involving black bears (Braunstein et al. 2020; TWRA 2023). Road systems are a known factor that negatively affects black bear populations in the southeastern US by disturbing habitats and altering bear behavior (Brody and Pelton 1989). Black bears prefer to travel along paved versus gravel roads, which affects survivability and increases the likelihood for bear-vehicle collisions (Reynolds-Hogland and Mitchell 2007). Road systems can be detrimental for black bears because of their large home ranges; for example, a single bear was reported traveling across four interstates, six 4-lane highways, 16 2-lane highways, and more than 100 paved roads in a three-month interval (Stratman et al. 2001). The implementation of structures to enhance landscape connectivity for black bears is vital to maintain congruence without human interference (Stratman et al. 2001), which is especially important because bears do not learn to avoid road systems with experience (Brody and Pelton 1989). Black bears also have preferences for road systems with less traffic (Brody and Pelton 1989), which have become limited for the species due to increased vehicle use after the Covid-19 pandemic (Ciuffini et al. 2023). Constructing underpasses at bridges in bear-vehicle collision hot spots could be important for reducing accidents (Eslinger and Morgan 2017); especially because road structures impact black bears on a population level instead of individually (Van Manen et al. 2012).

Elk (Cervus canadensis) were first reintroduced into eastern Tennessee in 2000-2003 with a total of 201 animals released (TWRA 2020, Kindall et al. 2011). In Tennessee, elk were estimated to have an average annual survivability of 0.79. There are more than 400 animals present in the state, and it was thought that additional translocations would be futile if survival rates did not increase (Kindall et al. 2011;

TWRA 2020). Some studies obtained similar results where Tennessee elk have been reported to have an 80.2% mean annual survival rate, with elk-vehicle collisions contributing to 11% of deaths (Kurth et al. 2023). Vehicle collisions are a factor contributing to elk mortality in Tennessee with collisions accounting for 8.1% of total mortality (Kindall et al. 2011). The yearly total economic benefit associated with the reintroduction of elk in Tennessee is over $2 million USD, providing significant economic benefits in the state (Chapagain and Poudyal 2020). Elk populations are still in the process of establishing themselves in Tennessee (Chapagain and Poudyal 2020) and mortalities due to vehicle collisions counteract the efforts to re-establish this species in the state and the associated economic benefits.

The current white-tailed deer population in the southeastern US is estimated to be larger than pre-Euro-American settlement (Hanberry and Hanberry 2020). There are more than 900,000 deer estimated to be in Tennessee alone, which is predicted to continually increase by 1-2% annually (TWRA 2005; Hanberry and Hanberry 2020). Increased deer populations have resulted in an abundance of negative human-deer interactions (Parkhurst 2002). In 2020, the state of Tennessee reported 6,549 motor vehicle crashes related to deer, resulting in over $90,000,000 in total damages (Tennessee Department of Safety and Homeland Security 2020). Wells (2005) found that the majority of WVCs resulting in human fatalities (77%) were caused by white-tailed deer and 99.2% of collisions are related to all deer species. Due to the growing white-tailed deer population in Tennessee and the number of associated deer-vehicle collisions in the state, there is a need to undertake mitigation measures to reduce the number of collisions.

Mitigation planning

Intensive evaluations of the effects mitigation strategies have on reducing WVCs are important for examining their effectiveness (Romin and Bissonette 1996). When assessing WVC effectiveness, mitigation planning requires studies that include an explicit hypothesis, longstanding data collection periods, as well as pre- and post-evaluations for effects on animals (e.g., structure use, (Hardy et al. 2003). Implementation of mitigation strategies should focus on targeting a specific animal species of interest and on a road-by-road basis during the design phase to effectively reduce WVCs (Gunson et al. 2011). Monitoring potential regions with increased animal use for mitigation structures before construction is vital to pinpoint areas which would be more readily used by animals. However, a key challenge in mitigation planning is having adequate and accurate data to identify where and to what extent mitigation measures could be beneficial. Once data is collected, use of spatiotemporal cluster analyses can be used to aid transportation coordinators, in determining mitigation structure type, length, and location and for wildlife hotspot identification, has proven to be an effective tool (Mountrakis and Gunson 2009). Additional information on data collection to inform mitigation decisions and a range of mitigation measures follows.

Improving wildlife-vehicle collision data collection

Much of the existing data on WVCs comes from incident reporting by transportation field crews or law enforcement officers. However, this data can be limited because many individuals do not report minor accidents and additional data from other means can be used to augment standard data collection efforts.

The use of citizen scientists (i.e., the public) to collect roadkill counts is a beneficial method for collecting large amounts of data to enlarge the range of wildlife species collected (Tiedeman et al. 2019). Shilling and Waetjen (2015) found that the inclusion of volunteer-collected data was taxonomically and spatially accurate enough to be used for WVC mitigation planning. Video surveillance data established to monitor wildlife usage and activity for WVC mitigation structures is important for evaluating continued effectiveness (Dodd et al. 2007). Using trail cameras with remote access spaced around 100 m away from structures to monitor wildlife use is an accepted method for observing crossing structure use and preferences based on habitat differences (Brennan et al. 2022). Cameras with flashes and infrared technology are necessary to monitor nocturnal wildlife species for WVC mitigation use (Hardy et al. 2003).

Data quality and agency collaboration. Lack of cooperation among agencies can reduce efficacy in improving data collection consistency and precision for best practices of WVC mitigation efforts and hot spot identification (Huijser et al. 2008). For example, a multistate survey used for reporting mitigation effects for deer found that eight states could not contribute due to inaccuracies in data (Romin and Bissonette 1996). Consistency in data collection over time is important for modeling and effectively evaluating usefulness of mitigation structures. Sullivan and Messmer (2003) noted fewer than 30% of agencies recorded and maintained longstanding WVC databases. Coordination and increased communication between agencies in reporting WVCs is an important step in maintaining quality data (D'Angelo et al. 2006; Huijser 2007). Cooperation, data sharing, funding, and collection uniformly among various agencies is vital to promote quality data collection (Hardy et al. 2003; Huijser

2007, Shilling et al. 2020). Standardized collection programs to implement cooperation between various agencies, which utilize uniformity in data retrieval, storage, reporting, sharing, and analyses, allows for higher quality data usage (Ament et al. 2021). Data validation and the use of CSV files or electronic data forms, which are routinely improved, can be used to ensure that data are correctly and easily shared among different agencies (Shilling et al. 2020). Finally, organizing multiple workshops and creating various trainings, infographics, or outreach materials could be a useful mechanism to inform and educate agency personnel on WVC data collaboration and consistency (Ament et al. 2021).

Reporting unaccounted-for roadkill. Sources for collecting WVC data are predominantly from police patrol reports, insurance claims, and carcass counts (Williams and Wells 2005; (Huijser, Marcel P., Meredith E. Wagner, Amanda Hardy, Anthony P. Clevenger 2007) Huijser et al 2008). The mortality rate for roadkill can be 12-16 times more than what is estimated by counting from vehicle collisions alone (Slater 2002). Vehicle encounters with wildlife are thought to be grossly underreported, which is due to crash databases excluding collisions with minor damage, nonreporting to authorities, scavengers removing carcasses, harsh environmental conditions, or wandering of injured wildlife away from roadsides (Sullivan and Messmer 2003; Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008). Wildlife-vehicle collisions that go unreported are often but not always those that involve minor damage or are less costly (Huijser et al. 2009). Additionally, the sustainability of a carcass on roadsides is often determined by the size of the animal and taxonomic group (Teixeira et al. 2013; Santos et al. 2016). It is important to survey roadsides at constant intervals to ensure carcasses are not being removed by scavengers or continuously destroyed by moving vehicles; increasing intervals between roadkill counts can cause inaccuracies in data collection due to missing data (Santos et al. 2011). Because mammals typically have larger body masses in comparison to amphibian or bird species, their carcasses remain detectable along roadsides for longer periods of time (Teixeira et al. 2013). For example, (Santos et al. 2011) found that roadsides should be checked every two days for the removal of carnivores before they become undetectable in the environment, whereas one-day intervals were recommended for birds and small mammals. Although animals with a total body mass less than 100g are less likely to persist on roadways, the median time carcasses are preserved on roadsides is 2.2 days (Santos et al. 2016). Carcass counts should be conducted slowly and training sessions completed for first time roadkill observers (Santos et al. 2016). Additionally, the use of correction factors should be implemented in roadside wildlife carcass counts to reduce biases due to animals wandering away from roadways to die after vehicle impact (Lee et al. 2021). Correction factors are calculated by taking into account biases between the number of carcasses found during surveys and the unreported carcasses found during foot counts (Lee et al. 2021). Another consideration would be double counting of carcasses by different individuals with larger animal carcasses remaining for days or weeks. Again, correction factors and proper training would minimize count errors.

Involvement of citizen science in WVC data collection can also be a useful tool for collecting enormous amounts of data over large areas with high abundances (Valerio et al. 2021), although participation in volunteer-collected WVC data will rely on extensive outreach programs to enhance public involvement (Shilling et al. 2020). Some countries are utilizing navigation applications to include roadkill for the public to report (Shilling et al. 2020). Reporting WVCs through mobile applications by transportation officials or the public can be an important tool to record collisions that would otherwise go unpublicized (Wilkins et al. 2019). Underreported incidents in addition to spatially biased data has the ability to severely disrupt model capabilities in predicting where WVCs occur (Snow et al. 2015). Underreported, spatially biased data is suggested to be a last resort and is not recommended for species with infrequent WVCs; however, increased reporting will enhance model predictive capabilities (Snow et al. 2015). Enhancing spatial precision, with the use of GPS coordinates, is also vital for improving data collections (Huijser 2007). One method that has proven to increase model accuracy is the use of mobile devices to record roadkill locations, reducing location error and transferability to reduce data entry errors (Olson et al. 2014). Additionally, the use of mobile applications to report WVCs is important because it can be immediately generated for spatial models (Shilling et al. 2020). Using volunteer-submitted images of roadkill is also a useful tool because GPS coordinates and species identification can be extracted from photographs (Shilling et al. 2020). Use of exact locations using smart phones instead of highway markers is a much more accurate method of data collection (Olson et al. 2014).

Wildlife-Vehicle Collision Hotspot Identification

Environmental hotspots. Wildlife-vehicle collisions occur due to road structures intersecting wildlife habitats used for breeding, foraging, or protection (Gunson et al. 2011); therefore, targeting sites associated with a particular species of interest is important for collision mitigation. Habitat criteria are important components for determining where mitigation structures should be implemented (Hurley et al. 2009). Forested and open environments surrounding road structures have been associated with increased ungulate-vehicle collisions (Gunson et al. 2011). Wildlife-vehicle collisions have been found to increase in agricultural or other cultivated landscapes (Valerio et al. 2021) because animals could be attracted to these landscapes in search of food resources. For example, (Chen and Wu 2014) found that animal-vehicle collisions were more likely to occur on roads encompassed by forested habitats on both sides of the road. The percentage of total forested areas predicted the number of WVCs for ungulate, avian, medium mammal, and small mammal wildlife in California, in which collisions increased as forested areas surrounding roads increased (Ha and Shilling 2018). Forested habitats with increased forest-field edge densities have been associated with increased deer-vehicle collisions (Farrell and Tappe 2007). Open and forested habitats near road structures have been associated with increased ungulate-vehicle collisions (Gunson et al. 2011). Fragmented forest habitats are also associated with increased WVCs for red deer (Saint-Andrieux et al. 2020).

Bashore et al. (1985) found that white-tailed deer-associated vehicle collisions increased along roadsides as the surrounding habitat became less forested and as woodland-field interfaces increased. Roadways are associated with edge habitats, due to the abrupt changes in habitat types along roadways, which could attract white-tailed deer ((Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008). Because white-tailed deer are less likely to migrate compared to other ungulate species and have large populations which are geographically ubiquitous across Tennessee (Resop et al. 2024), environmental variables associated with vehicle collisions for this species can be difficult to pinpoint. White-tailed deer were found to cross roads where there was forest cover in close proximity on the opposite side of the road (DeVault et al. 2020). White-tailed deer collisions have been associated with riparian habitats (Huijser, et al. 2008). Riparian or forested habitats, or gullies adjacent to roadsides, were associated with increased white-tailed deer vehicle collisions, which is thought to be due to deer using these habitats for feeding or cover (Finder et al. 1999).

Vehicle collisions with feral pigs (Sus scrofa) in South Carolina were associated with roads in close proximity to streams, bottomland hardwoods, or riparian habitats (Beasley et al. 2013). In France, feral pig-vehicle collisions were associated with less forested areas characterized with anthropogenic habitats such as agricultural or urban environments (Saint-Andrieux et al. 2020), whereas fewer feral pig-vehicle collisions were associated with roadsides neighboring managed pine plantations (Beasley et al. 2013). Forest management strategies used in surrounding nearby roadways were associated with a decrease in the number of feral pig WVCs (Saint-Andrieux et al. 2020). Vehicle collisions with medium-sized mammals also increased as roads intersected riparian habitats but occurred less often near agricultural fields (Conard and Gipson 2006). However, mesomammals were more likely to be involved in road collisions in areas comprised of more urban environments such as agricultural fields (Ha and Shilling 2018). Therefore, WVCs for species in specific habitats likely depends on site-specific criteria.

Nonstructural WVC Occurrence Hot Spots

Lighting. Establishing road characteristics associated with increased WVCs is vital for identifying regions where encounters should be mitigated. Roadsides with limited visibility are associated with increased white-tailed deer-vehicle collisions due to humans' inability to avoid crossing animals (Bashore et al. 1985). The majority of WVCs occur at night under dark or dim conditions, resulting in more than 70% of WVC occurring in dim conditions (Wilkins et al. 2019). The majority of white-tailed deer-vehicle collisions occur at night, which is thought to be due to drivers' inability to recognize deer in dark conditions (Stickles et al. 2022). Vehicle collisions associated with white-tailed deer along roadways also occur at night in unlit areas (VerCauteren, Kurt C., Nathan W. Seward, Michael J. Lavelle, Justin W. Fischer 2009). Sullivan (2011) found that dissipating light intensity throughout the day was associated with increased WVC. White-tailed deer vehicle encounters became more dangerous as distance increased to an oncoming vehicle; the use of high beam headlights increased white-tailed deer detection (Pakula et al. 2023). Increased lighting along roadways characterized as collision hotspots could be important for improving driver visibility and reducing white-tailed deer-vehicle collisions (Stickles et al. 2022).

Speed limit. Fedorca et al. (2021) found that increases in speed limits were associated with increased number of WVC along roadways; specifically, the amount of roadkill for large mammal species increased on high-speed limit sections. Increasing nighttime speed limits increased the relative risk that fatal WVC would occur (Sullivan 2011). Increased vehicle speeds along roadways are thought to be associated with increases in deer-vehicle collisions (Sullivan and Messmer 2003). Pakula et al. (2023) found that white-tailed deer vehicle encounters progressively became more perilous as automobile speed increased. Increased speed limits are more likely to result in wildlife-vehicle collisions due to longer braking distances and reduced driver reaction time (Pakula et al. 2023). Blackwell and others (2014) noted that white-tailed deer-associated vehicle collisions increased with increasing vehicle speeds due to the highly variable reaction of deer flight responses. They also found that neither increased approach speeds nor distance evoked earlier deer flight response times and that speed limits and speed reducing obstacles should be incorporated along road segments characterized as deer-vehicle collision hot spots. However, others found no association between deer-vehicle collisions and speed limit or traffic volume (Bissonette and Kassar 2008). Reducing speed limits were found to not be effective for reducing vehicle collisions with mule deer (O. hemionus); which was primarily thought to be due to the absence of motorists' compliance in reducing vehicles speeds (Riginos et al. 2022). Strict enforcement of speed limits in zones characterized as WVC hotspots could be an important measure to consider for collision reduction (Riginos et al. 2022). Reduced driving speeds at dusk and dawn and alerting drivers of areas with increased WVC could be important for augmenting driver response times to avoid animal encounters (Chen and Wu 2014).

Timing. Wildlife-vehicle collisions have also been associated with particular time periods and seasons, which often differ depending on the animal species (Bashore et al. 1985; Sullivan 2011). Increased number of collisions with wildlife at these times and seasons align with increased animal movement due to migration routes, mating, or hunting (Huijser, et al. 2008). Wildlife-vehicle collisions occur more commonly in early mornings from 0500-0900 and evenings from 1600-0000 (Huijser, et al. 2008). Wilkins et al. (2019) found collisions were reported to occur most often between 0500-0800 and 1700-2200 and in the months of October, November, and December. Temporal periods for WVC also differentiate based on a particular species activity pattern. For example, black bears become more active in the mornings when traffic is lower when using highway crossings (Van Manen et al. 2012) and elk were more likely to cross highway underpasses during crepuscular periods, with peak crossing times between 1700-2200 and 0400-0700 hours (Dodd et al. 2007). Wildlife-vehicle collisions were more likely to occur in the fall compared to any other season for medium-size mammals (Conard and Gipson 2006).

The Tennessee Department of Safety and Homeland Security (2020) noted half of reported white-tailed deer vehicle crashes occurred October-December and 79% between the hours of 1700-0700. Waring et al. (1991) found white-tailed deer activity along roadsides were reported anytime between 1700-0700 regardless of the amount of traffic or climatic conditions. (Muller et al. 2014) found the majority of deer-vehicle collisions occurred as individuals were beginning their commutes to work. This could be because white-tailed deer activity is primarily crepuscular and the majority of heavy traffic flows are reported between 0700-1859, coincidentally coinciding with deer-vehicle collisions (Stickles et al. 2022). Bissonette et al. (2008) also found deer-vehicle collision times to occur in the morning and evening around 1900-2400 to 0800 hours. Deer-vehicle collisions are more common in the autumn at dawn and dusk and 33% of deer vehicle collisions occur October-December, which coincide with deer activity patterns (Bashore et al. 1985; Bissonette et al. 2008; Stickles et al. 2022). Although the overall greatest deer-vehicle collision mortality occurred November and December. Male WVC mortality is noted to decrease in December as female mortality increased, but male mortality increased in spring and female mortality decreased (Puglisi, Michael J. 1974). This could be due to hunting pressure on males during hunting season.

County-level factors. Counties with increased human populations have increased WVC (Chen and Wu 2014). Wildlife-vehicle collisions were more likely to occur on county highways compared to interstate or municipal highways (Chen and Wu 2014). The majority of WVC hotspots with increased number of species can be determined by heavier traffic loads along roadways (Vance et al. 2018) and increases in road density are associated with an increase in WVC for roe deer (Capreolus capreolus) and feral pig (Saint-Andrieux et al. 2020). Increases in vehicle collisions with wildlife are also associated with low traffic densities in rural areas likely due to increased populations of wildlife (Wilkins et al. 2019). Urban environments with increased road, human population, and daily traffic densities have also been associated with increased WVC (Farrell and Tappe 2007). Determination of increased deer-vehicle collisions at the county level associated with increased human activity could be due to enhanced likelihood of human-wildlife interferences (Farrell and Tappe 2007).

Wildlife-vehicle collision mitigation in the southeastern US

In the southeastern region of the US, wildlife crossing structures are typically not designed specifically for animal crossing but are extensions of roadway construction (Donaldson 2007). In contrast, in western regions of the US, it is more common for wildlife mitigation structures to be specifically designed to guide wildlife across highways and oftentimes overpasses are implemented (Sawyer et al. 2016; Gagnon et al. 2022). Underpasses, created by structures such as bridges or box culverts, are often monitored for wildlife use in the US (Donaldson 2007). In Florida, underpasses with fencing are frequently used by white-tailed deer (Odocoileus virginianus), mountain lion (Puma concolor), raccoon (Procyon lotor), and bobcats (Lynx rufus);

however, American black bears (Ursus americanus, black bear) crossings remained sparse (Lob 2001). In North Carolina, underpasses with fencing were frequently used by white-tailed deer and moderately used by black bears (Mccollister and Van Manen 2010). In Virginia, underpasses with fencing adequately guided white-tailed deer and black bear under road structures (Donaldson and Schaus 2010). Additionally, the use of seasonal deer advisory messages to alert drivers to be aware of crossing deer proved to reduce deer-vehicle collisions in Virginia (Donaldson and Kweon 2019). However, Druta and Alden 2020 (2020) found that occasionally humans habituate or overlook animal waning systems, rendering them ineffective. In Tennessee, structures such as fencing, which is commonly used as a WVC mitigation method, are used to reduce deer exposure to crops (Harper 2002); however, the use WVC mitigation strategies have not been extensively evaluated in the state.

Wildlife-vehicle collision mitigation strategies

Driver awareness. Methods to increase motorist attentiveness on roadways could be an important strategy in reducing WVC (Stickles et al. 2022). Roadside animal detection systems, which aim to warn drivers of approaching wildlife on roads using flashing signage, have shown to be efficacious at preventing WVC (Grace et al. 2017). Animal detection systems along roadsides can be used to detect wildlife with sensors and warn drivers to approach with caution (Huijser et al 2008). Although costs-benefits for some integrated mitigation structures, such as the use of animal detection systems with fencing or jump-outs, are not cost effective overall, on road sections characterized as WVC hotspots, these mitigation strategies do exceed thresholds (Huijser et al. 2009). Druta and Alden (2020) found that a flashing deer crossing sign triggered by a buried cable animal detection system was almost 100% dependable in detecting ungulates and reduced white-tailed deer associated vehicle collisions by 75%. The use of animal detection systems as a standalone method for reducing ungulate related vehicle collisions are a cost-effective measure to reduce animal collisions; however, they may not be as effective as using fencing in combination with over or underpasses (Huijser et al. 2009). Use of warning devices is most important during periods when wildlife is moving more frequently or during periods of high traffic (Grace et al. 2017). Warning devices are noted to cause significant decreases in driver speeds when approaching wildlife warning signs were activated (Grace et al. 2017). Permanent signage representing areas where deer frequently cross roadsides are not cost-effective methods for mitigating white-tailed deer collisions because of human habituation (Sullivan and Messmer 2003).

Population density control

Wildlife densities are associated with WVCs. Higher deer densities are thought to be associated with increased WVCs along roadsides (Sullivan and Messmer 2003). Hunting is a method to reduce deer densities and human perceptions on harvesting deer to reduce property damage caused by deer-vehicle collisions increases their likelihood of accepting culling as a management regime (Parkhurst 2002). Although buck harvests are associated with overall deer population size, increasing the quota for does could reduce deer-vehicle collisions in the long run (Schwabe et al. 2002). However, deer reductions could also have a negative effect on hunter wellbeing (Schwabe et al. 2002). In urban areas, deer density significantly predicted the number of deer-vehicle collisions, which could be used as a representative for managing and reducing deer-vehicle interactions (Gkritza et al. 2010). Rural areas with large deer populations were associated with higher rates of deer-vehicle collisions (Bissonette et al. 2008). Yearly hunting harvests were associated with the total number of WVCs and could be used as a representative for wildlife population abundances (Saint-Andrieux et al. 2020). Methods proposed to reduce WVCs associated with wildlife densities include culling wildlife near roads and developed areas that serve as collision hot spots (Gkritza et al. 2010). Decreasing animal densities, associated with WVCs, by increasing hunter bag limits to cull nuisance game species is a method for collision reduction (Litvaitis and Tash 2008).

Lethal management. Muller et al. (2014) noted that white-tailed deer-vehicle collisions were related to deer harvests, in which deer-vehicle collisions were associated with the previous year's number of hunter killed deer. Additionally, reductions in deer herds, by implementing hunter harvests, resulted in decreases in deer-vehicle collisions and increases in deer-vehicle collisions occurred after harvests were removed (Muller et al. 2014). Because wildlife-vehicle collisions often occur in regions with high deer population densities (Cserkész et al. 2013); increased wildlife culling and proper deer management programs in regions with higher WVCs could be an important tool for reducing vehicle encounters (D'Angelo, G. J., D'Angel, J. G., Gallagher, G. R., Osborn, D. A., Miller, K. V., & Warren 2006) (Cserkész et al. 2013). Culling can be done by increasing deer quotas or bag limits for female deer in areas with high deer-vehicle collisions (Huijser, et al. 2008). Although controlled hunts bring in substantial amounts of revenue in the form of hunting licenses, etc., sharpshooting white-tailed deer over a bait is the most effective method to reduce deer abundance (Doerr et al. 2001). Reducing white-tailed deer herds by sharpshooting resulted in decreased deer-vehicle collisions, in which deer population reductions of 54%, 72%, and 76% caused 49%, 75%, and 78% reductions in vehicle collisions, respectively (Denicola and Williams 2008). Kilgo et al. (2020) found that culling white-tailed deer in forested areas adjacent to roadways was an effective method in reducing deer-vehicle collisions, with almost 40% yearly reduction in collisions. However, there was a seasonal effect on the ability of sharpshooting to reduce deer-vehicle collisions, in which spring deer removals reduced WVCs but autumn removals were not effective (Kilgo et al. 2020). Although deer culling is an effective measure of reducing deer-vehicle collisions, the economic justification for this mitigation strategy must be considered (Denicola and Williams 2008).

Fertility control. Birth control methods to reduce wildlife population, which would ultimately decrease WVCs, are becoming more sought after because culling is difficult with increasing urban environments and changing human perceptions (Massei 2023). Rutberg and Naugle (2008) found that there was no relationship between vehicle collisions and deer treated with porcine zona pellucida (PZP) immunocontraception vaccine; birth control usage stabilized deer populations which ultimately reduced deer-vehicle collisions on a 233-ha site in Maryland. However, one reason U.S. Department of Agriculture National Wildlife Research Center discontinued testing of PZP because the hormonal changes in deer were responsible for elongating the breeding season and rut, which ultimately increased the potential for deer movement and associated vehicle collisions (Miller et al. 2013).

Predator introduction. Decreases in WVCs can be accomplished by predators reducing prey abundances (O'Bryan et al. 2018). Predator recolonization to reduce deer densities has been recognized as a method to lessen WVCs, in which the introduction of mountain lions averted $1.1 million every year in deer-vehicle collisions in South Dakota (Gilbert et al. 2017). Similarly, the expansion of gray wolves (Canis lupus, wolves) into Wisconsin counties resulted in a 24% decrease in white-tailed deer-related vehicle collisions (Raynor et al. 2021). Wolves decreased WVCs by altering deer behavior contrary to reducing their abundance; resulting in wolves saving $10.9 million annually from deer-related vehicle encounters compared to $174,000 spent on wolf-related livestock deaths (Raynor et al. 2021). In France, it was estimated there was an average of nine wild boar and 30 roe deer consumed by each wolf, preventing WVCs and saving 2.4-7.8 million Euros in property damages (Sèbe et al. 2023).

Wildlife sensory mitigation methods

Olfaction. The use of mitigation strategies which target wildlife's sensory systems could provide a method of controlling wildlife-vehicle collisions in regions where construction of mitigation structures is impossible or to maintain ecosystem connectivity (Babińska-Werka et al. 2015, Fedorca et al. 2021). Many studies targeting wildlife senses have been proposed to reduce WVCs. For example, some research has focused on olfaction to deter wildlife from roadways. (Bíl et al. 2018) noted that the use of odor repellent Pacholek, a fatty acid derived from essential oils, caused a 26-43% decrease in large mammal-vehicle collisions, which included feral pig, roe deer, and red deer, on treated roads. Odor repellents provide a low-cost option for reducing WVCs, but they do require continued maintenance and care (Bíl et al. 2018). Additionally, the type of olfactory repellent and the concentration used are important factors to consider (Bíl et al. 2018). However, some researchers noted that the use of predator odor to repel deer away from roadways was not an effective tool at reducing roe and red deer-vehicle collisions (Elmeros et al. 2011). A lack of response of deer to odors could be due to increased habituation and or decreased responsiveness to predator odor stimuli (Elmeros et al. 2011).

Auditory. Some methods to reduce WVCs have targeted mammals' auditory perception. For example, wildlife warning whistles attached to vehicles to alert mule deer of an approaching automobile were found not to elicit a response (Romin and Dalton 1992). Deer whistles had no effect on reducing WVCs (Sullivan and Messmer 2003). (Valitzski et al. 2009) likewise reported there was no effective response to white-tailed deer in mitigating vehicle collisions using pure tone sounds known to be perceptible by white-tailed deer. Wildlife-collision mitigation devices using natural animal warning calls showed a 93-85% efficacy for reducing wildlife mortality for trains (Babińska-Werka et al. 2015). Although increased efficacy could have been due to a combination of auditory warning signals and vibrations from oncoming trains, this method of reducing WVCs for personal vehicles has not been tested (Babińska-Werka et al. 2015). Although there is concern that wildlife will habituate to auditory stimuli, researchers have found that wildlife did not become accustomed to the use of warning calls and these methods increased an animal escape reaction (Babińska-Werka et al. 2015).

Visual. Early tests of wildlife warning reflectors reported mixed efficacy for preventing WVCs (Brieger et al. 2016). Wildlife warning reflectors are installed onto roadside posts and consist of mirrors which send light through multicolored lenses, which direct vehicle headlights to warn deer (D'Angelo et al. 2006). There are some reports of wildlife habituating to reflectors and ultimately decreasing their efficacy (Benten et al. 2018). D'Angelo, et al. (2006) found that Strieter-Lite warning reflectors did not elicit an advantageous deer response and were not effective at preventing WVCs. Negative results for reflectors preventing WVCs could be due to them overwhelming the deer optical system (D'Angelo, et al. 2006). Other researchers also found that the inclusion of reflectors did not inhibit white-tailed deer from crossing roads and therefore reduce WVCs (Waring et al. 1991). Differences in reflector type or color is shown to have no effect on their ability to reduce WVCs (Benten et al. 2018). Sullivan and Messmer (2003) also found mirrors were perceived to have no effect on reducing WVCs on highways. Additionally, Romin and Bissonette (1996) found that states were using mitigation practices, such as mirrors or reflectors, which were previously found to not be effective strategies for reducing WVCs although no measures were taken to evaluate their usefulness. Although studies which used pre-post study designs reported the effect of wildlife warning reflectors on reducing WVCs, there is no consistent evidence that reflectors are able to effectively reduce WVCs by altering animals' response to approaching vehicles (Benten et al. 2018). In most instances, the use of reflectors to mitigate wildlife behavior resulted in an increase in WVCs (Benten et al. 2018). The use of reflectors to mitigate wildlife-vehicle collisions has been shown to be largely ineffective (Brieger et al. 2016). The use of vehicle lighting was shown to increase perceived risk of vehicle approach by white-tailed deer (Blackwell and Seamans 2009; DeVault et al. 2020). Specifically, a rear-facing light bar that increased overall frontal vehicle illumination greatly reduced "freezing" behavior by deer and therefore reduced dangerous deer-vehicle interactions (DeVault et al. 2020).

Wildlife collision mitigation structures

Species interactions. There is concern that predators might use collision mitigation structures as a method for capturing prey species. For example, some predators such as badger (Meles meles) have been reported to use overpasses for feeding (Van and Worm 2001). The prey-trap hypothesis suggests that predators use WVC mitigation structures for apprehension of prey; however, researchers found no hard evidence that predators use wildlife-crossing structures to their advantage (Ford and Clevenger 2010). Caldwell and Klip (2020) found that mule deer abstained from using highway underpasses that were frequently used by mountain lions and coyote (Canis latrans) preferred structures with higher abundances of prey species present. A variety of carnivore and herbivore species use mitigation structures at different time periods (Foster and Humphrey 1995) suggesting that predator-prey relationships or competition at these installations may be trivial. There is also a concern that interspecific or intraspecific competition between animals in territories could inhibit the use of WVC structures by wildlife. Often, differences in wildlife species compositions are seen using WVC mitigation structures which could be due to competition between wildlife species or abundance fluctuations (Van and Worm 2001). For example, mule deer are often seen preferring overpass structures (Simpson et al. 2016), but others have seen a preference for mule deer and underpasses when pronghorn (Antilocapra americana) frequently used overpasses (Sawyer et al. 2016).

Wildlife ecology and habituation. Accounting for different species' biological patterns which could affect their use of mitigation strategies is important for maintaining design efficacy. Vehicle collisions along roadways are often associated with white-tailed deer activity patterns (Sullivan 2011). Mitigation strategies that incorporate modifications of deer movement and behavior display promising results for evaluating program effectiveness (Romin and Bissonette 1996). For example, considering a targeted species' ecology can be important for knowing exactly where and when to implement a structure (Huijser et al. 2009).

Habitat choice or home range is critical for choosing mitigation structure locations because it can affect the likelihood that a species uses the structure (Huijser et al. 2009). The majority of road animal crossings are frequently done by a select few animals instead of collectively (Brody and Pelton 1989; Gulsby et al. 2011, Stickles et al. 2022). Design of overpass construction should consider long-standing ecological changes, such as landscape changes or animal movement patterns which could affect wildlife use of a structure over time (McGuire TM, Clevenger AP, Ament R, Callahan R, Jacobson S 2021). Large wildlife mitigation structure projects also require cooperation from landowners for long term effectiveness; for example, urbanization of landscapes near wildlife mitigation structures or in areas surrounding wildlife corridors could reduce structure use by wildlife (McGuire TM, Clevenger AP, Ament R, Callahan R, Jacobson S 2021). Planning for wildlife-crossing structures should include integration of wildlife population dynamics by monitoring trends in abundance and structure use to determine mitigation construction efficiency (Schmidt et al. 2021). Wildlife use of WVC mitigation structures change based on the time of year and geographical location (Edwards et al. 2022). Season has is a contributing factor on WVCs in which encounters were more likely to increase in colder months compared to warmer months or seasons (Chen and Wu 2014). Ungulates and feral pigs more frequently use WVC mitigation structures during breeding season compared with any other time of year (Van and Worm 2001), which could coincide with animal use of mitigation structures. Brunen et al. (2020) reported that wildlife used drainage culverts more frequently whenever moon luminosity increases, which could be due to animals' ability to see predators. Integration of ecological interactions between wildlife and their environment is an essential aspect in mitigation structure efficacy.

Wildlife habituation to WVC mitigation structures is also an important aspect to consider after construction. Habituation to mitigation structures can take up to several years (Clevenger and Waltho 2004, Schmidt et al. 2021) and fluctuations in structure use by ungulates are often associated with species habituation (Van and Worm 2001). Wildlife accustomed to constant vehicle traffic are less vulnerable to roadway disturbances compared to animals that are only exposed intermittently; for example, wildlife that habituated to roadway disturbances were more likely to use crossing structures in Alberta, Canada (Nojoumi et al. 2022). White-tailed deer grazing areas along roadsides influence deer movement in these areas compared to forest cover; for example, fencing within forested environments on roadsides where there is little forage and mostly tree cover reduced WVCs (Puglisi, Michael J. 1974; Bashore et al. 1985). White-tailed deer commonly feed in open habitats surrounding the right-of-way near roadsides (Waring et al. 1991). Elk passage along wildlife crossings increased as structures distance to forested environments increased (Clevenger and Waltho 2005). Ungulate and feral pig species are associated with increased WVCs as habitat patches increase across the landscape. This could be due to animal movements between habitat patches (Saint-Andrieux et al. 2020). Short-term intercept feeding, comprised of apples, alfalfa, and deer pellets, for deer in high-risk collision areas reduced WVCs (Wood and Wolfe 1988; Romin and Dalton 1992). This method would be a cost-effective strategy for reducing collisions for WVC hotspots during time periods when deer are more active (Wood and Wolfe 1988). Supplemental feeding of ungulates and feral pig caused an increase in use of WVC mitigation structures (Van and Worm 2001); temporary feeding, lures, or the inclusion of favorable forage could be used to attract wildlife to an area for crossing structure habituation (Goosem et al. 2005; Hou 2022). However, habituating wildlife to vehicle-collision mitigation structures using bait should be done with extreme caution due to potential negative health effects occurring from aggregating a large abundance of species in one location (Sorensen et al. 2014).

Large carnivore usage of crossing structures has been strongly associated with preferred habitat types (Clevenger and Waltho 2000). High-quality habitat near road systems were associated with frequent use of black bear near highways (Van Manen et al. 2012). For example, black bears commonly use paved roads during years with increased hard mast yield (Reynolds-Hogland and Mitchell 2007). Habitat factors strongly influence black bear road crossings. For example, they were more likely to use highway structures bordered by upland forested habitats and less likely in bottomland hardwoods (Hooker et al. 2016), whereas felids were found to increase crossing structure use as canopy cover increased (Schmidt et al. 2021). Large carnivore species are more likely to utilize underpasses as their distance to drainages decreases (Clevenger and Waltho 2000). Additionally, large carnivores are less likely to use underpasses with nearby human activity; therefore, structures focused on reducing WVCs for associated species should not be constructed near hiking or horseback riding trails (Clevenger and Waltho 2000).

Structure mitigation implementation. Implementation of WVC mitigation strategies requires careful planning to ensure adequate gene flow of wildlife populations and to avoid segregating habitats (Huijser, et al. 2008). Construction of mitigation structures should be determined by the particular region they are used in, and it is imperative that each is site specific (Vance et al. 2018). Consideration of mitigation structures at the beginning of roadway design phases can be important for reducing the overall cost for structure construction (Huijser et al. 2009). The use of less expensive materials and mass production for mitigation structure construction can be important methods for reducing costs (Huijser et al. 2009). The cost-benefit of long-term use for WVC mitigation structures outweighs the initial expenditure on these structures (Wilkins et al. 2019). Long term use of large WVC mitigation structures, such as under or over passes, are shown to have a 3.0 cost benefit ratio (Wilkins et al. 2019).

Fencing. Fencing along roadways near WVC hotspots can reduce wildlife-vehicle encounters by up to 80–99% (Huijser et al 2008; Clevenger et al. 2001). Survey responses found that nine of ten states reported fencing as an effective measure to reduce WVCs associated with deer (Romin and Bissonette 1996). Fencing has also been regarded as a cost-efficient mitigation method for reducing WVCs due to its effectiveness in preventing intrusion into roadways. Although fencing is regarded as an effective mitigation structure for wildlife species that do not prefer passages (Ascensão et al. 2013), fencing structures for carnivores have varied outcomes. In Canada, fence mitigation structures proved ineffective for black and grizzly bear (Ursus arctos) species, as they were seen to easily climb over them (Clevenger et al. 2001). Ford et al. (2022) also found that fencing was ineffective for large carnivores which was thought to be due to incursion into fence barriers. However, a North Carolina study used fencing with box culverts to guide black bear away from roadways (Jones et al. 2008). Coyotes can navigate underneath fencing at various gaps; however, this was resolved by burying barriers 1.5 m belowground (Clevenger et al. 2001). Buried fencing can mitigate increased WVCs for canine species that crawl over or under fencing structures and have small home ranges which do not enable them to reach underpasses (Mccollister and Van Manen 2010). Frequently maintained fences reduce the likelihood that WVCs occur due to white-tailed deer's inability to cross mitigation structures (Bashore et al. 1985); therefore, constant inspections for repair are vital to maintain fence efficacy.

Wildlife preferences for certain fence types can be important factors to consider for reducing WVCs. Short fencing lengths were not as effective at reducing white-tailed deer crossings at WVC hotspots compared to longer fence lengths (Gulsby et al. 2011). Fence length is often shortened for cost or aesthetic purposes; however, longer fence lengths are associated with collision reduction efficiency (Huijser et al. 2016). For example, fence lengths shorter than 5 km were less effective at preventing WVCs involving large mammal species, which included bear, feline, and deer species (Huijser et al. 2016). Gulsby et al. (2011) found that outrigger and 2.4 m tall fencing reduced white-tailed deer crossings by 90%; however, deer were found using fence ends for crossing at terminating fence endings at natural or man-made barriers. The use of deer-resistant Bump Gates along fence lines proved to be an effective measure for ensuring white-tailed deer did not cross onto roadways, these structures could be important in ensuring gates remained closed since they do not require the use of manual locking (VerCauteren et al. 2009). The combined use of fencing and wildlife detection systems were 30% more likely to reduce WVCs compared to other mitigation methods while considering cost effectiveness (Wilkins et al. 2019).

The use of jump outs in combination with fencing proved to be a reliable method for reducing WVCs (Edwards et al. 2022). Jump outs are structures which can be integrated with fencing to provide animals with a method for escape on roads or the right of way (Huijser et al. 2009). Deer were the most frequent wildlife species to use jumpout ramps, whereas mountain lions, black bears, and feral pigs did not use these structures (Jensen et al. 2018). Jensen et al. (2022) also found that black bear rarely used jumpouts. Wildlife fencing and jump out combinations provide low-cost thresholds for reducing WVC hotspots along roads (Huijser et al. 2009).

Fencing is typically combined with wildlife underpasses, overpasses, or jumpouts to ensure that wildlife can navigate between habitat types and do not crossroads (Huijser, et al. 2008). The inclusion of fencing in combination with multiple underpasses and/ or jump outs are often considered the most effective mitigation strategy for reducing WVCs (Edwards et al. 2022). Gagnon et al. (2015) found a 97% reduction in elk-vehicle collisions after the installation of heightened barbed wire fencing, to 2.4 m high, which directed elk towards crossing structures. Although heightened fencing reduced elk from crossing roadways, it was not as effective against deer (Gagnon et al. 2015). Wildlife-vehicle collisions decrease with the combination of an underpass and fencing structure, but collisions gradually increase with distance from the crossing structure (Mccollister and Van Manen 2010). Felids (i.e., feline species) are reported to increase crossing structure use as fence length increases (Schmidt et al. 2021). Fencing in combination with highway underpasses are an important tool for allowing large mammal species to cross fragmented habitat types without being funneled onto roadways (Foster 1995). Because the combination of fencing with other mitigations structures such as over or under passes or right of way escape ramps is more effective and allows for connectivity between habitats, there are virtually no circumstances when they should not be included together (Bissonette et al. 2008).

Huijser et al. (2016) found that 35% of ungulates that meandered near fence ends for foraging crossed roadways. There are more wildlife carcasses along roadsides with fences compared to non-fenced areas (Mccollister and Van Manen 2010), which could be due to wildlife getting trapped within the fenced road segments. Collisions are still shown to occur along fence line openings at interchanges because wildlife are funneled into the right-of-way by fence lines (Cserkész et al. 2013). Clevenger et al. (2001) also noted construction of V-shaped fence terminals to lead wildlife away from road structures after discovering increased WVCs for large mammals were nonrandomly distributed at the end of roadway fencing structures. Managing the fence ends, by stopping on slopes, structures, or angling inward, can be an important method of guiding wildlife back away from road structures (Huijser et al. 2015). Additionally, fence placement along roadways is an important aspect to consider; for example, fences that maintain a 30-125 m distance in addition to forest cover between road and fence structures are more likely to deter white-tailed deer crossings (Gulsby et al. 2011). Fencing placed within forested areas or installed more than 22.86 m from the nearest forested area has the lowest occurrence of deer WVCs (Puglisi et al. 1974). The reduction in deer collisions is most probably due to the existence of deer grazing areas available away from the fence roadside and the reduction of deer cover (Puglisi et al. 1974). Increases in WVCs with fencing structures are related to fences constructed at edge habitats or under 22.86 m yds from forested environments (Puglisi et al. 1974).

Other structures besides traditional fence types have been used as barriers to reduce WVC. For example, the placement of large boulders along roadsides can be used as a fence to deter ungulates from crossing into traffic (Huijser et al. 2008). Additionally, plastic sheets were constructed at rail openings to deter ungulates from entering roadways from the right-of-way, by creating a slick surface, but remained ineffective at reducing wildlife traffic (Clevenger et al. 2001). The use of guard rails can also be used as a structural barrier; for example, these structures could act as fences after a study reported reduced WVCs on roads with guard rails (Pagany and Dorner 2019). The use of cattle or wildlife guards in place of gaps between fences could be a cost-effective method to reduce wildlife traffic onto roadways for select wildlife species (Allen et al. 2013). Guard structures were more than 85% effective at reducing deer crossings onto road systems and presents a cost-effective measure to mitigate WVCs in comparison to electric matting (Allen et al. 2013). Wildlife guards are more effective for hoofed animals compared to those with paws; for example, guard structures were more effective at reducing ungulate (>85%) crossings compared to black bear (33-46%) or coyote (33-55%) (Allen et al. 2013). Guard structures could be a useful tool to use when woven-wire fencing cannot be applied. VerCauteren, et al (2009) found that deer guards initially reduced white-tailed deer passage onto roadways but effectiveness diminished overtime as deer learned to jump and / or walk over them. Extending the length of deer guards could be an effective method in preventing white-tailed deer from jumping over them onto roadways (VerCauteren et al 2009).

Underpasses. Highway underpass structures are used by a variety of large wildlife species, such as black bear, white-tailed deer, coyote, and panther and can be used when the construction of other crossing types are inaccessible (Foster 1995). Underpass structures for mitigating WVCs are also known to provide an economic benefit compared to overpasses (Huijser et al. 2009). Underpasses are a less costly option compared to overpasses; however, there is differentiation in wildlife use for these mitigation structures (Sijtsma et al. 2020). White-tailed deer often use roads for foraging and crossing even when underpasses were implemented. Due to deer not solely selecting underpasses, the addition of fencing or other forms of mitigation are recommended (Donaldson et al. 2016). Although carnivore use of crossing structures is associated with habitat variables, ungulate use is associated with structural variables (Clevenger and Waltho 2000). Ungulates are less likely to use underpasses with increased underpass openness and underpass width, but more likely to use underpasses with increased noise (Clevenger and Waltho 2000). Ungulates prefer underpasses compared to culverts or overpasses (Huijser et al. 2008; Mata et al. 2008). Large mammals prefer underpasses with less openness and human activity (Clevenger and Waltho 2000). Large mammal underpasses are recommended to be greater than 10 m and greater than 4 m in height (Clevenger and Huijser 2011). Mule deer in a California study were found to almost solely prefer large underpasses compared to culverts (Jensen et al. 2018). Mule deer preferences for underpasses are associated with shorter lengths and larger passage openings (Ng et al. 2004). Underpass structural characteristics, such as openness and width, strongly influenced the likelihood that mule deer used them (Gordon and Anderson 2003). Additionally, future underpasses should be at least 6 m wide, 2.4 m tall, and contain an openness ratio of 0.8 or more (Gordon and Anderson 2003). Elk were more likely to cross underpasses as their length decreased (Clevenger and Waltho 2000). Changes in underpass construction, such as elimination of concrete walls and widening floor lengths to 32 m, increased the likelihood that elk used collisions mitigation structures (Dodd et al. 2007). White-tailed deer and raccoon are more likely to use highway underpasses that are drier (Foster 1995). Underpasses with at least a 3.65-meter height were more likely to be used by white-tailed deer and these structures were frequently used by coyote too (Donaldson 2007). Given the propensity of black bears to cross highways where underpasses are installed, fencing in combination to underpasses may be an important method for reducing black bear mortality around road structures (Van Manen et al. 2012).

Different wildlife species also have preferences for the location of underpasses; for example, coyotes and bobcats were more likely to avoid passages close to developed environments (Ng et al. 2004). Taking advantage of under-construction roadways for implementation of underpasses is a cost-effective method for their construction, contrary to building them into roadways (Ford et al. 2017). White-tailed deer and elk increase underpass use and foraging unless flight responses were initiated by passing vehicles; therefore, use of sound and light proof walls may increase wildlife use of these structures (Nojoumi et al. 2022).

Drainage culverts. Drainages near road structures have also been associated with increased WVCs involving ungulates (Clevenger et al. 2001); therefore, use of drainage culverts as collision mitigation structures could substantially reduce WVCs. Drainage culverts can be used as an alternative to incorporating costly wildlife passages; however, preferences for these structures differs by wildlife species (Sparks and Gates 2012). White-tailed deer are more likely to use drainage box culverts that are wider, higher, and longer (Sparks and Gates 2012). Mule deer avoid small culverts and instead prefer open and wide underpasses (Ng et al. 2004). Short and small culverts, < 0.6 m in diameter, with the absence of excess organic debris are important for the selection of smaller wildlife species such as bobcat or striped skunk (Mephitis mephitis) (Chen et al. 2021). Additionally, the use of polyethylene materials hindered the movement of wildlife species across drainage culverts for medium and small mammals whereas there was no difference between steel and concrete (Brunen et al. 2020).

In Maryland, culverts without fencing were not trafficked as highly by white-tailed deer as those with fencing (Sparks and Gates 2012). Brunen et al. (2020) found that drainage culverts were not sufficiently used by wildlife species to crossroad structures and suggested using fencing and wildlife passages instead. Only water tolerant species, including white-tailed deer, raccoon, and American mink (Neovison vison), were seen crossing the culverts and found to frequent drainage ditches. Felids typically avoid crossing structures with even minimal amounts of standing water present (Schmidt et al. 2021). Others noted drainage culverts that imitate waterways are important for a diversity of wildlife species crossing road structures (Donaldson 2007). Although black bears used a mixed variety of culvert types, consisting of 1.2 m x 1.2 m concrete culverts to large underpasses, they more frequently used small culverts, compared to drive through culverts or large underpasses (Jensen et al. 2018). The frequency of black bear and wolf crossing mitigation structures increased as the distance to drainage increased (Clevenger and Waltho 2005), meaning that drainage culverts may not be the best choice for structures aimed at bear passage. However, box culverts were cost effective structures for single bear crossings across roadways (Ford et al. 2017). Mountain lions were only found to use box culverts when crossing road structures (Jensen et al. 2018).

Overpasses. Overpasses are above-grade constructions which span over roadways (Brennan et al. 2022). Large mammal species, such as deer and elk, prefer overpasses compared to underpasses (Huijser et al. 2008; Simpson et al. 2016). These structures can prevent one to three WVCs per mile annually and maintain up to an 8 km treatment area (Sugiarto 2023). Ungulates and feral pig are frequently encountered species on wildlife overpasses, especially during rut in autumn and winter (Van and Worm 2001). Feral pigs primarily use overpasses and occasionally underpasses but do not prefer culverts (Mata et al. 2008). Elk are more likely to utilize crossing structures as structure width, height, and openness increase, but less likely to cross as length and noise increase (Clevenger and Waltho 2005). Canine use of WVC mitigation structures, specifically wolf, increased as structure width, height, openness and human activity increased (Clevenger and Waltho 2005). Deer frequently used WVC mitigation structures with increased width, height, openness, and human interference (Clevenger and Waltho 2005). Although grizzly bears use larger, more open structures such as overpasses, box culverts had similar use and cost effectiveness (Ford et al. 2017). Wildlife-vehicle collision mitigation structures that are more open are associated with a decrease in black bear crossings; however, crossing increased as structure length increased (Clevenger and Waltho 2005). Because black bear preference is more closely associated with closed structures, mitigation strategies to reduce WVCs for this species might be better addressed with wildlife underpasses. Although overpasses are reported to be more effective at reducing WVCs in comparison to culverts, the targeted species should be considered because animal preferences vary by crossing structure (Sugiarto 2023).

Determination of overpass dimensions is a critical consideration when designing WVC mitigations structures (Brennan et al. 2022) and disregard for wildlife biologists' recommendations for structure characteristics would render them ineffective (Clevenger and Waltho 2005). Wide overpasses often have a more diverse array and higher abundances of species crossing (Brennan et al. 2022). Wildlife preferences for overpasses are often related to structure width; for example, 40-50 m width is acceptable for large mammals (Van and Worm 2001). Longer overpass structures should be wider to accommodate species preferences; the ratio for width to length is 0.8 (Brennan et al. 2022). The use of overpasses by large mammals is often associated with structure width; for example, large wildlife species are more likely to use overpasses 100 m in width or wider compared to 10-50 m (Kusak et al. 2009). Additionally, large carnivores are six times more likely to cross wide overpasses compared to those 10-15 m in width (Kusak et al. 2009). The recommended overpass dimensions for crossing structures are 50-70 m to accommodate wildlife preferences (Clevenger and Huijser 2011), which refers to the width available for wildlife movement not outer width (Brennan et al. 2022).

Although proven to be an effective method for reducing WVCs, the construction of wildlife overpasses alone can be exceedingly costly, anywhere from 5–15 million dollars USD or more, compared to other reduction methods (McGuire 2000; Brennan et al. 2022). However, it is estimated that wildlife overpass structures can potentially save anywhere from $235,000-443,000 yearly, due to their benefits in reducing WVCs (Sugiarto 2023). Traditional wildlife bridges can be costly, and wildlife can have difficulty habituating to their construction (Clevenger and Waltho 2004; Ament et al.

2022). However, cost effective strategies for wildlife overpasses could include the use of buried bridges that use manufactured materials and soil to support structure weight, which are 33-67% lower in cost (McGuire et al. 2021). The cost of maintenance should also be considered for overpass construction. Buried bridges are more cost effective in the long run with minor maintenance requirements (McGuire et al. 2021). Multiuse bridges which accommodate wildlife and human movement, with the use of funnel fencing, could also be a cost-effective overpass method, but should not be considered for species that do not tolerate humans (McGuire et al. 2021). The use of beveling at the end of bridges, or the use of angling fill material at the structure ends, can be a cost-effective strategy because they permit differential settlement (McGuire et al. 2021). Cost effective materials for overpass construction include the use of geosynthetic reinforced soil or high-density expanded polystyrene geofoam blocks, contrary to the use of steel or concrete (McGuire 2021).

Recommendations

Mitigation planning is an important aspect to consider before WVC strategies are implemented. During this stage, strategy effectiveness is evaluated to determine when, where, and what methods should be used to reduce WVCs.

The data collected to ensure effective mitigation planning is directly related to data quality which is improved by the following (also see Table AP1):

- Mobile devices and use of GPS for enhanced spatial accuracy and decreased location data entry error
- Video surveillance
- Agency coordination, standardization of collection programs, and data sharing for improved data quality
- Frequent carcass counts and correction factors to improve data accuracy
- Citizen science to increase data collection
- Workshops and training to improve collection performance and coordination

Findings from this literature review suggest WVC mitigation strategies should be chosen based on a targeted species of interest within a particular hotspot. It is imperative to select mitigation practices based on species' preferences and biology for the best results. Additionally, considerations for different wildlife species interactions and habituation to mitigation strategies are imperative to ensure effective use. Wildlife-vehicle collision hotspot identification is vital for potential habitat management and determining where to implement collision reduction strategies. Characteristics associated with locations of high-volume WVCs can be environmental, structural, or nonstructural and include the following (see Table AP2):

Structural

- Increased collisions at fence ends, highway interchanges, drainage areas, areas of high roadway density, and roads with limited visibility
- Decreased collisions occur with fewer road networks (or reduced number of roads)

Nonstructural

- Increased collisions in areas with heavy morning and evening traffic flows, increased animal densities, increased human population densities, increased speed limit, during the months of October-December, and spring and winter seasons
- Decreased collisions with increased motorist attentiveness, strict enforcement of speed limits, nearby human disturbance, driver warnings or alerts of animals in the area, reduced driving speeds at dusk and dawn, and obstacles to reduce vehicle speed

Environmental

- Increased collisions with autumn and winter seasons; dawn and dusk; unlit locations; forested, edge, developed, riparian, and fragmented habitats
- Decreased collisions with forest management strategies, agricultural landscapes, and areas associated with human disturbances

It can be difficult to determine a suitable mitigation structure because species preference for crossing structures can sometimes vary by study (Sawyer et al. 2016; Simpson et al. 2016). Wildlife-vehicle collision mitigation techniques should use a variety of crossing structures to target various wildlife species preferences to increase connectivity among habitats patches separated by roads (Clevenger and Waltho 2005). Researchers have previously speculated that mitigation structures suitable for more selective species should be acceptable designs for less sensitive animals too (Kusak et al. 2009). Among decisions for structure characteristics, height, width, length, etc., considerations must be made for a particular location or habitat to adhere to wildlife preferences (Brennan et al. 2022). Mitigation strategies are vital for directly reducing WVCs by implementing wildlife population control, nonstructural, and structural methods and directly include the following (also see Table AP3):

Population control

- Decreased collisions with predator establishment, increased doe harvests, immuno-contraceptives, sharpshooting, deer herd management, increased hunter bag limits, and culling in forested areas adjacent to roadways in spring

Nonstructural

- Decreased collisions with animal detection systems, odor repellents, acoustic warning devices using natural calls, and short-term intercept feeding

Structural

- Decreased collisions with underpasses with fencing; partial fencing; fencing within forested environments on roadsides; large underpasses; cattle guards; guard rails; fences placed 30-125 m from roadways; fence ends stopped on slopes, structures, or angled inward; jumpouts; heightened barbed wire fencing; V-shaped fence terminals; underpasses; cattle guards with extended lengths; and fencing in combination with jumpouts

Increased mitigation structure use by wildlife is associated with decreased structure length; crossing structure width, height, and openness increase; increased human interference near crossing structure; wide overpasses with a width of 100 m or wider; overpass dimensions 50-70 m; longer fence lengths; underpasses with shorter lengths; underpasses with larger passage openings; fences ending at natural or man-made barriers; underpasses with at least a 3.65 m height; dry underpasses; underpasses at least 6 m wide and 2.4 m tall dimensions; underpass lengths widened to 32 m; underpasses with sloped earthen sides; underpasses with short lengths; increased underpass openness;; culverts short in length; overpass width 40-60 m; structure with width, height, and openness increased; decreased human activity around underpass; box culverts with fencing; box culverts with absence of excess organic debris; box culverts with increased width, height, and length; underpasses with sound and light-proof walls; and underpasses greater than >10 m width and >4 m in height.

Suggested method	Outcome	Species	Source
Mobile devices	Reduced error location, decrease data entry time, 10% data entry error reduction, enhance data transferability, enhance spatial accuracy	All species	(Olson et al. 2014, Wilkins et al. 2019)
Video surveillance	Improved assessment of mitigation structure use	Elk	(Dodd et al. 2007)
Carcass counts every two days	Improved data accuracy	Carnivores	(Santos et al. 2011, 2016)
Carcass counts every other day	Improved data accuracy	Small animals 9 kg or less	(Santos et al. 2011)
Searching roadkill by foot	Improved data accuracy	All species	(Slater 2002, Teixeira et al. 2013)
Evaluating mitigation strategy effectiveness	Improved assessment of mitigation structure use	*Odocoileus* spp.	(Romin and Bissonette 1996)
Coordination among agencies	Improved data quality	All species	(Huijser, Marcel P., Meredith E. Wagner, Amanda Hardy, Anthony P. Clevenger 2007)
Remote trail camera surveillance	Improved assessment at crossing structures	All species	(Brennan et al. 2022)
The use of GPS coordinates	Improved data quality and spatial accuracy	All species	(Huijser, Marcel P., Meredith E. Wagner, Amanda Hardy, Anthony P. Clevenger 2007)
Increased roadkill reporting	Improved model predictive capabilities	Moose and white-tailed deer	(Santos et al. 2016, Snow et al. 2015)
Data sharing among agencies	Improving data collection programs	All species	(Huijser, Marcel P., Meredith E. Wagner, Amanda Hardy, Anthony P. Clevenger 2007)
Data collection uniformity among agencies	Improving data collection programs	All species	(Huijser, Marcel P., Meredith E. Wagner, Amanda Hardy, Anthony P. Clevenger 2007)

Inclusion of volunteer and citizen science data	Improving data collection programs	All species	(Shilling et al. 2020, Shilling and Waetjen 2015, Valerio et al. 2021)
Documenting roadkill with mobile photos	Improved data quality and spatial accuracy	All species	(Shilling et al. 2020)
Data format uniformity among agencies	Improving data collection programs	All species	(Shilling et al. 2020)
Consistency in reporting roadkill	Improved data quality	*Odocoileus* spp.	(Romin and Bissonette 1996)
Explicit hypothesis, longstanding data collection periods, and pre and post evaluations for animal structure use	Enhance mitigation planning	All species	(Hardy et al. 2003)
Cameras with flashes and infra-red technology	Enhanced structure monitoring	All species	(Hardy et al. 2003)
Citizen science collected data	Large collections of data	All species	(Tiedeman et al. 2019)
Spatiotemporal cluster analyses	Improved assessment for mitigation structure location	All species	(Mountrakis and Gunson 2009)
Road by road basis for determining mitigation structure use	Improved selection for mitigation structure	All species	(Gunson et al. 2011)
Standardized collection programs	Improving data collection programs	All species	(Ament et al. 2021)
Routinely improved electronic data forms	Improving data collection programs	All species	(Ament et al. 2021)
Organizing workshops and trainings	Improving worker performance and productivity	All species	(Ament et al. 2021)
Correction factors	Improve data accuracy	All species	(Lee et al. 2021)

Table AP2. Structural, nonstructural, and environmental characteristics that are associated with wildlife-vehicle collisions for the Tennessee Department of Transportation.

Hotspot type	Suggested method	Outcome	Species	Source
Nonstructural	Increased human populations density	Increases wildlife-vehicle collisions	All species, white-tailed deer	(Chen and Wu 2014, Farrell and Tappe 2007)
	Increased animal densities	Increases wildlife-vehicle collisions	Feral pig	(Cserkész et al. 2013)
	Increased path distance to an oncoming vehicle within 6.5 m	Increases wildlife-vehicle collisions	White-tailed deer	(Pakula et al. 2023)
	High beam headlights	Increase wildlife detection	White-tailed deer	(Pakula et al. 2023)
	Morning	Increases wildlife-vehicle collisions	White-tailed deer	(Muller et al. 2014)
	Increased traffic densities	Increase wildlife detection	White-tailed deer, all species	(Farrell and Tappe 2007, Vance et al. 2018)
	Early mornings 0500-0900 and evenings 1600-0000	Increases wildlife-vehicle collisions	All species	(Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008)
	Increase motorist attentiveness on roadways	Decreases wildlife-vehicle collisions	White-tailed deer	(Stickles et al. 2022)
	Heavy traffic flows between 0700-1859	Increases wildlife-vehicle collisions	White-tailed deer	(Stickles et al. 2022)

	Dawn and dusk	Increases wildlife-vehicle collisions	*Odocoileus* spp.	(Bissonette et al. 2008)
	Hours 1900-2400 to 0800	Increases wildlife-vehicle collisions	*Odocoileus* spp.	(Bissonette et al. 2008)
	Crepuscular periods, with peak crossing times between 1700-2200 and 0400-0700 hours	Increases wildlife-vehicle collisions	Elk	(Dodd et al. 2007)
	Hours 0500-0800 and 1700-2200	Increases wildlife-vehicle collisions	All species	(Wilkins et al. 2019)
	Morning	Increased use of overpass	Black bear	(Van Manen et al. 2012)
	Spring and winter	Increases wildlife-vehicle collisions	White-tailed deer	(Bashore et al. 1985)
	Hours 1700-7-00	Increase activity along roadsides	White-tailed deer	(Tennessee Department of Safety and Homeland Security 2020, Waring et al. 1991)
	Rut	Increase mitigation structure use	Ungulates and feral pig	(Van and Worm 2001)

	Increased speed limit	Increases wildlife-vehicle collisions	All species, White-tailed deer, *Odocoileus* spp.	(Blackwell et al. 2014, Fedorca et al. 2021, Pakula et al. 2023, Sullivan and Messmer 2003)
	Increased approach speeds	Not associated with increased deer flight response times	White-tailed deer	(Blackwell et al. 2014)
	Distance of approaching vehicle to deer	Not associated with increased deer flight response times	White-tailed deer	(Blackwell et al. 2014)
	Vehicle speed reducing obstacles	Decreases wildlife-vehicle collisions	White-tailed deer	(Blackwell et al. 2014)
	Speed limit	No effect on wildlife-vehicle collisions	*Odocoileus* spp.	(Bissonette and Kassar 2008)
	Traffic volume	No effect on wildlife-vehicle collisions	*Odocoileus* spp.	(Bissonette and Kassar 2008)
	Reducing speed limits	No effect on wildlife-vehicle collisions	Mule deer	(Riginos et al. 2022)
	Strict enforcement of speed limits	Decreases wildlife-vehicle collisions	Mule deer	(Riginos et al. 2022)
	Reduced driving speeds at dusk and dawn	Decreases wildlife-vehicle collisions	All species	(Chen and Wu 2014)
	Nearby human disturbance	Decreased wildlife use	Felines	(Ng et al. 2004)
	Alerting drivers of collision hot spots	Decreases wildlife-vehicle collisions	All species	(Chen and Wu 2014)

Structural	Fence ends	Increases wildlife-vehicle collisions	Ungulates	(Clevenger et al. 2001, Huijser et al. 2016)
	Highway interchanges	Increases wildlife-vehicle collisions	Roe deer	(Cserkész et al. 2013)
	Railways parallel to highways	Increases wildlife-vehicle collisions	Feral pig	(Cserkész et al. 2013)
	Drainages	Increases wildlife-vehicle collisions	Ungulates	(Clevenger et al. 2001)
	Increased road densities	Increases wildlife-vehicle collisions	White-tailed deer, roe deer, feral pig	(Farrell and Tappe 2007, Saint-Andrieux et al. 2020)
	Drainage systems near underpass	Increase wildlife use	Large Carnivore	(Clevenger and Waltho 2000)
	County highways	Increases wildlife-vehicle collisions	All species	(Chen and Wu 2014)
	Roadsides with limited visibility	Increase wildlife detection	White-tailed deer	(Bashore et al. 1985)
	Regions with fewer road networks	Decrease wildlife detection	All species, ungulates	(Chen and Wu 2014, Ha and Shilling 2018)
Environmental	Autumn	Increases wildlife-vehicle collisions	White-tailed deer, medium size mammals	(Bashore et al. 1985, Bissonette et al. 2008, Conard and Gipson 2006, Stickles et al. 2022)
	Winter	Increases wildlife-vehicle collisions	All species	(Chen and Wu 2014)
	Dawn and dusk	Increases wildlife-vehicle collisions	All species	(Chen and Wu 2014)

	Forested landscapes on both sides of the road	Increases wildlife-vehicle collisions	All species	(Chen and Wu 2014)
	Increased forested habitat	Increases wildlife-vehicle collisions	Ungulates	(Ha and Shilling 2018)
	Gullies adjacent to roadsides	Increases wildlife-vehicle collisions	White-tailed deer	(Finder et al. 1999)
	Reduced forested habitat	Increases wildlife-vehicle collisions	White-tailed deer	(Bashore et al. 1985)
	Forested and open environments surrounding roads	Increases wildlife-vehicle collisions	All species	(Gunson et al. 2011)
	Forest management strategies	Decreases wildlife-vehicle collisions	Feral pig	(Saint-Andrieux et al. 2020)
	Decreased proximity to forest cover on the opposite side of the road	Increases wildlife-vehicle collisions	White-tailed deer	(DeVault et al. 2020)
	Fragmented habitats	Increases wildlife-vehicle collisions	Red deer, ungulates, and feral pig	(Saint-Andrieux et al. 2020)
	Riparian habitats	Increases wildlife-vehicle collisions	White-tailed deer, medium size mammals, and feral pig	(Beasley et al. 2013, Conard and Gipson 2006, Finder et al. 1999, Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008)

	Increased total forest	Increases wildlife-vehicle collisions	All species	(Ha and Shilling 2018)
	Forested habitats with increased edge densities	Increases wildlife-vehicle collisions	White-tailed deer	(Farrell and Tappe 2007)
	Decreased percentage of pine plantations	Increases wildlife-vehicle collisions	Feral pig	(Beasley et al. 2013)
	Developed habitats	Increases wildlife-vehicle collisions	Feral pig, medium size mammals, all species	(Ha and Shilling 2018, Saint-Andrieux et al. 2020, Valerio et al. 2021)
	Open and forested habitats near roads	Increases wildlife-vehicle collisions	Ungulates	(Gunson et al. 2011)
	Distance to forested environments increased	Increases wildlife-vehicle collisions	Elk	(Clevenger and Waltho 2005)
	Upland and Bottomland habitats	Increase use of highway structures	Black bear	(Hooker et al. 2016)
	Increased canopy cover	Increase crossing structure	Felids	(Schmidt et al. 2021)
	Agricultural landscapes	Decreases wildlife-vehicle collisions	Medium size mammals	(Conard and Gipson 2006)
	Decreased proximity to forested areas	Increases wildlife-vehicle collisions	White-tailed deer	(Finder et al. 1999)
	Public recreational land	Increases wildlife-vehicle collisions	White-tailed deer	(Finder et al. 1999)

	Distance to habitat	Increases wildlife-vehicle collisions	Moose	(Hurley et al. 2009)
	Summer season	Increase underpass use	Elk	(Dodd et al. 2007)
	Deer grazing areas along roadsides	Increases wildlife-vehicle collisions	White-tailed deer	(Puglisi, Michael J. 1974)
	Dark or unlit conditions	Increases wildlife-vehicle collisions	All species, white-tailed deer	(Stickles et al. 2022, Sullivan 2011, VerCauteren, Kurt C., Nathan W. Seward, Michael J. Lavelle, Justin W. Fischer 2009, Wilkins et al. 2019)
	Developed habitat near mitigation structure	Decreased wildlife use	Bobcat, coyote	(Ng et al. 2004)
	Nearby human disturbance	Decreased wildlife use	Felines	(Ng et al. 2004)
	Moon luminosity increases	Increased use of drainage culverts	Medium and small size mammals	(Brunen et al. 2020)
	Crossing structure distance to drainage increased	Increased wildlife use	Black bear and wolf	(Clevenger and Waltho 2005)

Table AP3. Mitigation practices, using population control, structural, and nonstructural methods, to reduce wildlife-vehicle collisions for the Tennessee Department of Transportation.

Structure type	Suggested mitigation method	Outcome	Species	Source
Population control	Culling in forested areas adjacent to roadways in spring	Decreases wildlife-vehicle collisions	White-tailed deer	(Kilgo et al. 2020)
	Culling in forested areas adjacent to roadways in autumn	No effect on wildlife-vehicle collisions	White-tailed deer	(Kilgo et al. 2020)
	Immunocontraceptives	Decrease deer population	White-tailed deer	(Rutberg and Naugle 2008)
	Sharpshooting	Decreases wildlife-vehicle collisions	White-tailed deer	(Denicola and Williams 2008 Doerr et al. 2001)
	Deer herd management	Decreases wildlife-vehicle collisions	White-tailed deer	(D'Angelo, G. J., D'Angel, J. G. Gallagher, G. R., Osborn, D. A., Miller, K. V., & Warren 2006)
	Increased population density	Increases wildlife-vehicle collisions	All species	(Cserkész et al. 2013)
	Yearly hunting harvests	Associated with total wildlife-vehicle collisions	Red deer	(Saint-Andrieux et al. 2020)
	Increasing hunter deer quotas or female bag limits	Decreases wildlife-vehicle collisions	All species	(Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008)
	Hunter harvests	Decreases wildlife-vehicle collisions	White-tailed deer	(Muller et al. 2014)
	High deer densities	Increases wildlife-vehicle collisions	*Odocoileus* spp.,	(Bissonette et al. 2008, Sullivan and Messmer 2003)

	Increasing hunter bag limits	Decreases wildlife-vehicle collisions	Game species	(Litvaitis and Tash 2008)
	Immunocontraceptives	Increases wildlife-vehicle collision	white-tailed deer	(Miller et al. 2013)
	Cull wildlife near collision hot spots	Decreases wildlife-vehicle collisions	White-tailed deer	(Gkritza et al. 2010)
	Increased doe harvests	Decrease wildlife-vehicle collisions	White-tailed deer	(Schwabe et al. 2002)
	Predator establishment	Decreases wildlife-vehicle collisions	White-tailed deer, feral pig, and roe deer	(Gilbert et al. 2017, Gulia-Nuss et al. 2016, Raynor et al. 2021, Sèbe et al. 2023)
Nonstructural method	Reflectors	No effect on wildlife-vehicle collisions	All species; White-tailed deer	Benten et al. 2018; Waring et al. 1991; Brieger et al. 2016; D'Angelo et al, 2006
	Increased noise near overpass	Decrease overpass use	Elk	(Clevenger and Waltho 2005)
	Deer whistles	No effect on wildlife-vehicle collisions	*Odocoileus* spp., mule deer	(Romin and Dalton 1992, Sullivan and Messmer 2003)
	Mirrors	No effect on wildlife-vehicle collisions	*Odocoileus* spp.,	(Sullivan and Messmer 2003)
	Permanent warning signage	Not cost-effective measure for wildlife-vehicle collisions	White-tailed deer	(Sullivan and Messmer 2003)
	Animal detection systems	Decreases and cost-effective measure for wildlife-vehicle collisions	All species, ungulates, white-tailed deer	(Druta and Alden 2020, Grace et al. 2017, Huijser et al. 2009, Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008)

	Vehicle-Mounted Sound-Production System	No effect on wildlife-vehicle collisions	White-tailed deer	(Valitzski et al. 2009)
	Acoustic warning device using natural calls	Decreases wildlife-vehicle collisions	All species	(Babińska-Werka et al. 2015
	Increasing speed limit	Increases wildlife-vehicle collisions	Moose	(Hurley et al. 2009)
	Pacholek odor repellents	Decrease between 26-43% can be expected	Feral pig, roe deer, and red deer	(Bíl et al. 2018)
	Speed limit	No effect on wildlife-vehicle collisions	*Odocoileus* spp.,	(Bissonette and Kassar 2008
	Traffic volume	No effect on wildlife-vehicle collisions	*Odocoileus* spp.,	(Bissonette and Kassar 2008
	Predator odor repellents	No effect on wildlife-vehicle collisions	Roe and red deer	(Elmeros et al. 2011)
	Short term intercept feeding	Decreases wildlife-vehicle collisions	*Odocoileus* spp., White-tailed deer, ungulates, and feral pig	(Romin and Bissonette 1996 Van and Worm 2001, Wood and Wolfe 1988)
Structural method	Underpass with fencing	Decreases wildlife-vehicle collisions	White-tailed deer, large mammal species, black bear	(Donaldson et al. 2016, Foster 1995, Van Manen et al. 2012, Mccollister and Van Manen 2010)
	Increased crossing structure length	Decrease wildlife use	Elk	(Clevenger and Waltho 2005
	Crossing structure width, height, and openness increased	Increase wildlife use	Canine, *Odocoileus* spp.	(Clevenger and Waltho 2005

Increased human interference near crossing structure	Increase wildlife use	*Odocoileus* spp.	(Clevenger and Waltho 2005)
Crossing structure with more open space	Decrease wildlife use	Black bear	(Clevenger and Waltho 2005)
Increase crossing structure length	Increase wildlife use	Black bear	(Clevenger and Waltho 2005)
Wide overpasses	Higher abundance and species richness	All species	(Brennan et al. 2022)
Overpass width 40-50 m	Increase wildlife use	Large mammals	(Van and Worm 2001)
Overpasses width 100 m or wider	Increase wildlife use	Large mammals	(Kusak et al. 2009)
Wide overpasses	Increase overpass use	Large carnivores	(Kusak et al. 2009)
Overpass dimensions 50-70 m	Increase wildlife use	Large mammals	(Clevenger, A.P., Huijser 2011)
Fencing within forested environments on roadsides where there is little forage and mostly tree cover	Decreases wildlife-vehicle collisions	White-tailed deer	(Bashore et al. 1985, Puglisi, Michael J. 1974)
Fencing	Decreases wildlife-vehicle collisions	All species	(Clevenger et al. 2001, Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008, Jones et al. 2008)
Partial fencing	Decreases wildlife-vehicle collisions	Small mammal	(Ascensão et al. 2013)

	Fencing	No effect on wildlife-vehicle collisions	American black bear	(Clevenger et al. 2001, Ford et al. 2022)
	Burying fence barriers	Decrease fence crossings	Canine	(Clevenger et al. 2001, Mccollister and Van Manen 2010)
	Frequently maintained fences	Decrease fence crossings	White-tailed deer	(Bashore et al. 1985)
	Short fencing length	Increases wildlife-vehicle collisions	white-tailed deer	(Gulsby et al. 2011)
	Longer fence lengths	Decreases wildlife-vehicle collisions	Bear, feline, and ungulates	(Huijser et al. 2016)
	Outrigger and 2.4 m fencing	Decreases wildlife-vehicle collisions	White-tailed deer	(Gulsby et al. 2011)
	Fence ending at natural or man-made barriers	Decreases wildlife-vehicle collisions	White-tailed deer	(Gulsby et al. 2011)
	Deer-resistant Bump Gates along fence lines	Decreases wildlife-vehicle collisions	White-tailed deer	(VerCauteren, Kurt C., Nathan W. Seward, Michael J Lavelle, Justin W. Fischer 2009)
	Fencing in combination with jumpouts	Decreases wildlife-vehicle collisions	All species, ungulates	(Edwards et al. 2022, Huijser et al. 2009)
	Jumpouts	Decreases wildlife-vehicle collisions	Mule deer	(Jensen, Alex et al. 2018)
	Jumpouts	No effect on wildlife-vehicle collisions	Black bear	(Jensen et al. 2022)
	Heightened barbed wire fencing	Decreases wildlife-vehicle collisions	Elk	(Gagnon et al. 2015)
	Heightened fencing	No effect on wildlife-vehicle collisions	*Odocoileus* spp.	(Gagnon et al. 2015)

Longer fence lengths	Increase crossing structure use	Felids	(Schmidt et al. 2021)
V-shaped fence terminals	Decreases wildlife-vehicle collisions	Large mammals	(Clevenger et al. 2001)
Fence ends stopped on slopes, structures, or angled inward	Decreases wildlife-vehicle collisions	All species	(Huijser, Marcel P., Angela V. Kociolek, Tiffany D.H. Allen 2015)
Fences placed 30-125 m from roadway	Decreases wildlife-vehicle collisions	White-tailed deer	(Gulsby et al. 2011)
Large boulders along roadsides	Decreases wildlife-vehicle collisions	Ungulates	(Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008)
Slick plastic sheet	No effect on wildlife-vehicle collisions	Ungulates	(Clevenger et al. 2001)
Guard rails	Decreases wildlife-vehicle collisions	All species	(Pagany and Dorner 2019)
Cattle guards	Decreases wildlife-vehicle collisions, initially decreases until animals habituate	White-tailed deer, *Odocoileus* spp.	(Allen et al. 2013, VerCauteren, Kurt C., Nathan W. Seward, Michael J. Lavelle, Justin W. Fischer 2009)
Large underpasses	Decreases wildlife-vehicle collisions	Mule deer	(Jensen, Alex et al. 2018)
Cattle guards with extended lengths	Decreases wildlife-vehicle collisions	White-tailed deer	(VerCauteren, Kurt C., Nathan W. Seward, Michael J. Lavelle, Justin W. Fischer 2009)

	Small culverts compared to drive through culverts or large underpasses	No effect on wildlife-vehicle collisions	Black bear	(Jensen, Alex et al. 2018)
	Fences constructed at edge habitats	Increases wildlife-vehicle collisions	White-tailed deer	(Puglisi, Michael J. 1974)
	Fence located less than 22.86 m from forested habitat	Increased wildlife-vehicle collisions	White-tailed deer	(Puglisi, Michael J. 1974)
	Underpasses	Decreases wildlife-vehicle collisions	Black bear, white-tailed deer, coyote, ungulates, and panther	(Foster 1995, Huijser, M., McGowen, P. Fuller, J., Hardy A., Kociolek, A., Clevenger, A Smith, D., and Ament 2008, Mata et al. 2008)
	Increased underpass openness and width	Decrease wildlife use	Ungulates	(Clevenger and Waltho 2000
	Underpasses with shorter lengths	Increase wildlife use	Mule deer	(Ng et al. 2004)
	Underpasses with larger passage openings	Increase wildlife use	Mule deer	(Ng et al. 2004)
	Underpasses at least 6 m wide and 2.4 m tall	Increase wildlife use	Mule deer	(Gordon and Anderson 2003
	Underpass length decreased	Decrease wildlife use	Elk	(Clevenger and Waltho 2000
	Underpass length widened to 32 m	Increase wildlife use	Elk	(Dodd et al. 2007)
	Dry underpasses	Increase wildlife use	White-tailed deer and raccoon	(Foster 1995)

Underpasses with at least a 3.65 m height	Increase wildlife use	White-tailed deer and coyote	(Donaldson 2007)
Underpasses near developed habitats	Decrease wildlife use	Coyote and bobcat	(Ng et al. 2004)
Decrease human activity around underpass	Increase wildlife use	Large mammals	(Clevenger and Waltho 2000)
Decrease underpass openness	Increase wildlife use	Large mammals	(Clevenger and Waltho 2000)
Underpasses greater than >10 m width and >4 m in height	Increase wildlife use	Large mammal	(Clevenger, A.P., Huijser 2011)
Underpass with sound and light proof walls	Increase wildlife use	White-tailed deer and elk	(Nojoumi et al. 2022)
Box culverts with increased width, height, and length	Increase wildlife use	White-tailed deer	(Sparks and Gates 2012)
Box culverts smaller in size	Decrease wildlife use	Mule deer	(Ng et al. 2004)
Box culverts with absence of excess organic debris	Increase wildlife use	Bobcat or striped skunk	(Chen et al. 2021)
Short and small culverts, <0.6 m in diameter	Increase wildlife use	Bobcat or striped skunk	(Chen et al. 2021)
Box culverts with fencing	Increase wildlife use	White-tailed deer	(Sparks and Gates 2012)
Drainage culverts	Suitable for wildlife use	White-tailed deer, raccoon, and American mink	(Brunen et al. 2020)
Drainage culverts with water accumulation	Decrease structure use	Felids, raccoon, and American mink	(Brunen et al. 2020, Schmidt et al. 2021)

	Overpasses	Suitable for passage	Mule deer, ungulates, feral pig	(Huijser, M., McGowen, P. Fuller, J., Hardy, A., Kociolek, A., Clevenger, A., Smith, D., and Ament 2008, Mata et al. 2008, Simpson et al. 2016, Van and Worm 2001)
	Structure width, height, and openness increased	Increased wildlife use	Elk	(Clevenger and Waltho 2005)
	Overpasses with 0.8 width to length ratio	Increased wildlife use	Large mammals	(Brennan et al. 2022, Gordon and Anderson 2003)
	Overpass width 40-60 m	Increase wildlife use	All species	(Brennan et al. 2022)
	Culverts < 6.0 cm in diameter	Increase wildlife use	Striped skunks, rock squirrel, bobcat	(Chen et al. 2021)
	Culverts short in length	Increase wildlife use	Striped skunks, rock squirrel, bobcat	(Chen et al. 2021)
	Culverts without soil accumulation	Increase wildlife use	Striped skunks, rock squirrel, bobcat	(Chen et al. 2021)
	Drainage culverts made from polyethylene materials	Decrease structure use	Raccoon and American mink	(Brunen et al. 2020)
	Underpasses with minimum height 3.6 m	Increase wildlife use	White-tailed deer	(Donaldson 2007)
	Underpass openness increased	Increased wildlife use	Elk	(Dodd et al. 2007)
	Underpass with short length	Increased wildlife use	Elk	(Dodd et al. 2007)
	Underpass with sloped earthen sides	increased wildlife use	Elk	(Dodd et al. 2007)

	Passing vehicle induced flight behavior	decreased underpass use	White-tailed deer, elk	(Nojoumi et al. 2022)
	Underpass with increased nearby human disturbance	Increased wildlife use	Coyote	(Ng et al. 2004)
	Underpasses with increased length	Decrease wildlife use	Mule deer	(Ng et al. 2004)
	Underpasses with decreased diameter	Decrease wildlife use	Mule deer	(Ng et al. 2004)
	Selection of overpass contrary to culvert	Increase wildlife use	All species	(Sugiarto 2023)