GEORGIA DOT RESEARCH PROJECT 22-34

Final Report

BRIDGE AND CULVERT DESIGNS FOR REDUCED WILDLIFE-VEHICLE CONFLICTS AND IMPROVED CLIMATE RESILIENCY: PHASE I

Georgia Department of Transportation

Office of Performance-based Management and Research
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November 2023

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This report describes the first phase of a comprehensive project to address the critical issue of Wildlife Vehicle Conflicts (WVCs), which average over 14,000 crashes and cost more than $850M per year in Georgia. With a focus on integrating hydraulic design principles with wildlife passage, this Phase I study conducted a preliminary and systematic literature review, extracting key insights into the ecological and structural variables that underpin best practices for reducing WVCs while facilitating wildlife movement. Notable findings include the enduring relevance of certain core ecological variables and a convergence of best practices for two groups of animals: medium / large-bodied mammals, and herpetofauna / small mammals. Results of the preliminary literature review suggest that there is sufficient knowledge to move forward with developing design guidelines for multi-objective hydraulic structures that better convey floods, reduce WVCs, and improve aquatic connectivity. Design modifications for flood and sediment conveyance under climate change are in accordance with several modifications that also reduce WVCs and promote aquatic connectivity. Building upon these insights, Phase II of the project is poised to enhance road safety, ecosystem connectivity, and infrastructure resilience through development of hydraulic design standards, integration of climate change considerations, spatial prioritization of structure enhancements and replacements, and recommendations tailored for the Georgia Department of Transportation (GDOT). By merging ecological knowledge with innovative engineering of wildlife friendly, climate-ready structures, this project aspires to forge a path toward safer and more sustainable transportation infrastructure in Georgia.</td></tr>
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GDOT Research Project 22-34

Final Report

BRIDGE AND CULVERT DESIGNS FOR REDUCED WILDLIFE-VEHICLE CONFLICTS AND IMPROVED

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Contract with
Georgia Department of Transportation

In cooperation with
U.S. Department of Transportation
Federal Highway Administration

November 2023

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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EXECUTIVE SUMMARY

Wildlife vehicle conflicts (WVC) average over 14,000 crashes and cost more than $850M per year in Georgia (FHWA 2023). Our research team has undertaken a Phase I study to identify opportunities to simultaneously improve road safety, reduce wildlife vehicle conflicts (WVC), effectively ensure water and debris conveyance capacity, enhance ecosystem connectivity, and reduce costs and maintenance requirements for the Georgia Department of Transportation (GDOT). The Phase I study is comprised of three objectives:

- Perform a preliminary literature review of best practices (including floodplain relief culverts, staged barrels, shelving, and vegetation / non-fencing directive techniques) for integrating hydraulic design with wildlife passage for reduced WVCs in different GA regions.
- Based on the preliminary literature review, provide GDOT with a brief prospectus on the potential practices that have the highest likelihood of reducing WVCs and improving safe flood conveyance; and
- Develop a Phase II research project scope for GDOT with the details of a research project and with potential objectives.

The preliminary literature review, as outlined in this report, serves as the foundation for a comprehensive two-phase project. The project's overarching aim is to address the critical issue of WVC by integrating design of climate robust hydraulic structures with design for effective wildlife passage, including large mammals.

PRELIMINARY LITERATURE REVIEW HIGHLIGHTS

This report primarily focuses on reviewing current knowledge of hydraulic structures that enhance wildlife passage, with emphasis on making roads safer for both animals and people while improving ecological connectivity. First, we carefully reviewed reports, papers, and different research sources using systematic review and snowball sampling techniques. We narrowed it down from a preliminary 757 publications related to reducing WVCs and improving hydraulic structures to the 177 most important publications for further analysis. This detailed review forms the foundation of our work by helping us identify and understand potential opportunities for designing hydraulic structures that reduce WVCs.

FINDINGS

Our research revealed some key insights on the most relevant design variables and appreciable convergence in the literature on structure characteristics that support passage of different types of animals. First, we found that certain recommendations for building wildlife passages have garnered sustained support for the past twenty years. These ideas include emulating natural environments, making passages shorter when possible, using the appropriate cross-sectional dimensions and a clear zone, including top openings where feasible, using natural materials and cover, and managing fencing and vegetation to increase utilization. In any case, this recommendation should take into account road design criteria as the clear zone restriction (between 7 and 10 ft) (American Association of State Highway and Transportation Officials 2011), and the ability of potential target species to handle the vehicle noise and human presence.

Second, our review showed that what works best can change depending on the location and type of animal. One-size-fits-all solutions are elusive, and "best practices" should be flexible to fit the context and objectives for locations. In general, the literature review indicated a broad need for more rigorous studies examining specific situations to improve wildlife passage guidelines, as well as follow-up monitoring of the performance of innovative structure designs.

In general, recommended best practices and design principles in the scientific literature lend themselves to grouping by two main species groups: 1) medium to large mammals, and 2) herpetofauna and small mammals (Table ES1). To facilitate the safe movement of medium to large mammals, tailoring structures to target species and their habitat preferences is vital. Fenced medians, open-top designs, natural substrate, dry paths or ledges, vegetation, noise reduction, and human restriction are also key considerations. For herpetofauna and small mammals, we recommend employing structures shorter than 82 ft (25 meters) where feasible, which can be shortened with headwalls or variable widths, including fenced medians for multi-roadway crossings, increasing natural sky exposure with open-top features, and maintaining natural substrate. Additionally, 3 to 10 ft (1-3m) wide dry paths or ledges, cover objects, railings or logs, and strategically placed vegetation can enhance these passages, along with measures to minimize noise. Recognizing that many herpetofauna migrate perpendicular to water bodies and managing bat passage to prevent guano buildup are important considerations. Fencing best practices are also presented and discussed in the main body of the final report.

In general, consideration of a structure that allows passage for a wider range of organisms based on the specific site context would address different size species and should be considered as a design optimization criterion. However, the applicability of the identified best practices will require specific contextual analysis to ensure consistency between innovative design approach and permitting requirements and operational standards.

Results of the preliminary literature review suggest that there is sufficient knowledge to move forward with developing design guidelines for multi-objective hydraulic structures that reduce WVCs, better convey floods, and improve aquatic connectivity. Design modifications for flood and sediment conveyance under climate change are in accordance with several modifications that also reduce WVCs and promote aquatic connectivity. Building upon these insights, Phase II of the project will improve road safety by identifying the risk of road flooding due to changes in the flow regime, such as debris jams caused by undersized structures, and effects of floods, ponding, and debris on structure susceptibility to failure, ecosystem connectivity, and infrastructure resilience through robust design (see Appendix II for Phase II details). It will encompass the development of hydraulic design standards, the integration of climate change considerations, spatial prioritization if structure enhancements and replacements, hydraulic design integration, and recommendations tailored for the Georgia Department of Transportation (GDOT). By merging ecological wisdom knowledge with innovative engineering of wildlife friendly, climate-ready structures, this project aspires to forge a path toward safer and more sustainable transportation infrastructure in Georgia.

Table ES1. Attributes of hydraulic structures that facilitate connectivity along aquatic habitats (wetlands, ponds, lakes, streams, or rivers) or between aquatic and terrestrial habitats.

Species Group	Best Practices
Medium to Large Mammals	• Best structure dimensions and attributes will depend on target species. **Consider structures that can accommodate multiple species** by including attributes for smaller species within larger, more open structures. ○ Species adapted to open spaces likely prefer more open. ○ Species that take refuge within structurally complex habitats may be more likely to use narrower structures. • **Include fenced medians** for structures crossing multiple roadways (e.g., divided highways). Fencing parallel to the direction of the structure in the median can ensure that animals already transiting the culvert system do not emerge half-way and enter the median. • **Maximize natural sky exposure** by incorporating open-top design features like slots or open grates. • **Maintain natural substrate** by using an open bottom, placing natural substrate in the structure, or burying the bottom (open bottom structures best facilitate the passage of wildlife). • **Include 3-10 ft (1-3-meter)-wide dry paths** or ledges that maintain a clear line of sight along each side of water body or through rip rap. Paths / ledges should remain dry under all but the most annual high flow. • **Include vegetation at the entrance** and within the structure (type and dimensions of vegetation will depend on target wildlife and could match natural vegetation in area). • **Minimize noise** (e.g., vehicular traffic) by maintaining vegetation near the entrance. • **Restrict human passage.**

Herpetofauna and Small Mammals	• **Length < 82 ft (25m)** [can be shortened by installing headwalls and varying width]. • **Include fenced medians** for structures crossing multiple roadways (e.g., divided highways). • **Maximize natural sky exposure** by incorporating open-top design features like slots or open grates. • **Maintain natural substrate** by using an open bottom, placing natural substrate in the structure, or burying the bottom (open bottom structures best facilitate the passage of wildlife). • **Include 3-10 ft (1-3-meter)-wide dry paths** or ledges that maintain a clear line of sight along each side of water body or through rip rap. Paths / ledges should remain dry under all but the most extreme flow events. • **Include cover objects** such as flat rocks or woody debris that do not obstruct the dry path or line-of-sight. • Consider inclusion of railings or logs that extend beyond the entrance to the structure to facilitate passage of scansorial and arboreal species. • Include vegetation at the entrance and within the structure (type and dimensions of vegetation will depend on target wildlife and could match natural vegetation in area). • **Minimize noise** (e.g., vehicular traffic) by maintaining vegetation near the entrance. • **Restrict human passage**. • Many herpetofauna migrate “perpendicular” [not parallel] to water bodies to access higher terrestrial habitats that do not flood and are critical to their life cycle. Structures using the attributes above but oriented along key migration paths between aquatic and terrestrial habitats may be needed to reduce wildlife vehicle collisions for these taxa. • Passage and presence of bats should be carefully managed to reduce the buildup of guano along dry paths.

PHASE II SCOPE AND RECOMMENDATIONS

The Phase I study sets the stage for a comprehensive Phase II project to enhance road safety, ecosystem connectivity, and infrastructure resilience. For this final report, we have divided Phase II of the project into two complementary lines of effort and timelines based on resource availability and time horizon, hereafter referred to as Phases II-a and II-b. Appendix II of this report includes a Phase IIa proposal for an initial set of tasks to be completed in the near term. Overall, the key elements of a Phase II scope include:

1. **Design Standards:** Development of hydraulic design standards focusing on culvert designs that reduce WVCs, account for changing environmental conditions, and enhance hydraulic performance.
2. **Climate Change Integration:** Reviewing existing culvert design standards within the context of climate change and aligning hydraulic performance with innovative WVC reduction strategies.
3. **Spatial Prioritization:** Creating a spatial prioritization framework and decision support toolbox, considering ecological, safety, and infrastructure factors for targeted interventions.
4. **Hydraulic Design Integration:** Applying geomorphic simulations to design case studies and HEC-RAS modeling, aiming to simultaneously achieve multiple goals, including WVC reduction and ecosystem connectivity.
5. **Recommendations for GDOT:** Offering recommendations to enhance the GDOT hydraulic design manual, addressing ecological suitability and practical implementation.

6. **Training:** Conducting workshops for GDOT to explore practical approaches, supported by real-world case studies to integrate hydraulic design with sediment and debris conveyance, organism passage, and innovative WVC reduction techniques.

This Phase I study lays the groundwork and bodes well for a comprehensive Phase II project that provides design recommendations for simultaneously achieving multiple objectives: reduced WVCs, safe flood and debris conveyance under climate change, and improved aquatic connectivity. Innovative designs that achieve all three objectives can increase safety, build climate resilience and reduce costs and maintenance requirements. As a result of this Phase I study, we conclude that there is sufficient knowledge to move forward with developing design guidelines for multi-objective structures. It is also apparent that many of the design modifications for flood and sediment conveyance under climate change (e.g., increasing rainfall intensity) are in accordance with several modifications that also reduce WVCs and promote aquatic connectivity. Building upon these insights, Phase II of the project is poised to enhance road safety, ecosystem connectivity, and infrastructure resilience through development of hydraulic design standards, integration of climate change considerations, spatial prioritization of structure enhancements and replacements, and recommendations tailored for GDOT. By merging ecological knowledge with innovative engineering of wildlife friendly, climate-ready structures, this project aspires to forge a path toward safer and more sustainable transportation infrastructure in Georgia.

CHAPTER 1. INTRODUCTION

Bridge and culvert design primarily involves safely passing floods and debris while minimizing instability and maintenance requirements. However, innovative bridge and culvert designs also have the potential to reduce wildlife-vehicle conflicts (WVCs) by facilitating the safe passage of wildlife beneath roadways. An estimated 1-2 million crashes between motor vehicles and large animals occur annually in the U.S., causing approximately 200 human deaths, 26,000 injuries, and at least $8 billion in property damage and other costs (Pew 2021). Georgia is among the 20 states with the highest risk of WVCs (State Farm 2020).Current bridge and culvert design methods do not include guidance on incorporating elements that simultaneously reduce the likelihood of WVCs while improving hydraulic performance and climate resilience to achieve a higher level of public safety. Further, permitting of structures by environmental agencies is sometimes delayed by wildlife passage concerns. Thus, there is an opportunity to concurrently address these concerns while enhancing public safety and infrastructure resilience.

PROBLEM STATEMENT

The traditional hydraulic design standards of waterway crossing structures like bridges and culverts are mainly based on hydrodynamic modeling of peak flow that the structure drains. Likewise, culverts in rural areas are typically designed based on flow calculated using a rainfall intensity of at least a 50-year return period (Nuannukul, Phumiphan, and Kangrang 2021). However, a warmer climate and anthropogenic changes have resulted in higher riverine flows due to rainfall pattern changes and increased severity of storms (Groisman, Knight, and Karl 2001). Therefore, integrating climate change approaches into design methods is necessary to enhance these structures' resilience.

According to the Savannah District's Note of the 2021 Nationwide Permit Regional Conditions, the U.S. Army Corps of Engineers recognizes the need for a comprehensive approach to culvert design, especially in light of climate change. Under these regional conditions, culvert replacement or installation requirements on perennial streams generally require culverts to match (or under specific situations exceed) the typical width of the stream channel. Also, they must to handle flows above bankfull without causing flooding or disrupting the natural hydrology of adjacent areas, and be installed at a relatively flat gradient to allow substrate to colonize the culvert's interior and maintain natural flow velocity (USCE 2021). This approach in concordance to the US. Fish and Wildlife Service, aims to the aquatic ecosystem connectivity, but also, represents an opportunity to simultaneously benefit environmental science, and engineering, particularly by improving wildlife passage and reducing wildlife-vehicle collisions (WVCs).

Aside from the urgent necessity of climate adaptation measures, many other factors, such as the increasing demand for mobility of people and goods, and the desire to reduce vehicle maintenance costs, suggest that public transportation networks must be improved. According to the latest infrastructure report (American Society of Civil Engineers 2022), most hydraulic structures in the United States have been graded as a "C," indicating that further maintenance procedures related to replacement or structural improvements are required in the near future. This scenario has allowed for the opportunity to assess the viability of analyzing co-benefits associated with environmental issues such as WVCs.

Linear infrastructure and traffic have an ecological effect on individual wildlife, populations, communities, and landscapes (van der Grift, van der Ree, and Jaeaer 2015). One of the most relevant is the barrier to movement due to natural habitat fragmentation. Forming gaps in habitat can modify the movement patterns of wildlife and likely increase wildlife mortality. Therefore, researchers have been trying to identify a solution over the past two decades that takes all aspects into consideration, including habitat fragmentation, barrier movement, WVCs, and economic losses.

Several worldwide studies have documented successful road crossing designs using under-and overpasses techniques and identified the benefits of implementing different mitigation measures (Clevenger and Waltho 2003; Glista, DeVault, and DeWoody 2009; Rytwinski et al. 2016; Marangelo 2019; Brunen, Daguet, and Jaeger 2020; Drasher and Murdoch 2021; Warnock-Juteau et al. 2022; Santos et al. 2022). However, these studies lack crucial elements to assess these approaches, such as the cost of implementation, operation, and maintenance. For example, the overpass structure, which is a terrestrial animal crossing structure that has been broadly implemented in Canada and Europe (Glista, DeVault, and DeWoody 2009), has a high cost associated with its construction and maintenance, while large animals only use it sporadically, resulting in a low cost-benefit ratio. On the other hand, recent studies on underpass structures, specifically culverts, have shown a high potential for used by various wildlife species at crossroads (Rodriguez, Crema, and Delibes 1996; Clevenger and Waltho 2003). By incorporating improvements into their designs to allow animal passage, these structures may be used as a mitigation measure (Marangelo 2019).

Implementing mitigation measures for reducing WVCs needs to integrate the analysis of several factors that potentially affect the ability of a crossing structure to facilitate wildlife movements (Glista, DeVault, and DeWoody 2009). Some of these factors can be grouped into two categories: ecological variables (e.g., noise level tolerance, reproductive species cycles, distance to the ecological hotspot edges, animal sensitivity to human presence) and structural variables (e.g., slope, openness ratio, length, presence of water, substrate type, dimension) (Warnock-Juteau et al. 2022; Clevenger, Chruszcz, and Gunson 2001; Grilo and Klar 2015; Glista, DeVault, and DeWoody 2009). Consequently, a systematic approach is lacking to determine the optimum combination of parameters that enhance hydraulic performance while providing a safe wildlife passage to reduce WVCs and provide resilient infrastructure adaptation.

GOALS AND OBJECTIVES

Phase I research aims to develop and scope a Phase II research project that identifies and details win-win opportunities for simultaneously enhancing culvert hydraulic performance and safe wildlife passage for reduced WVCs, focusing on the species and regions of Georgia.

The integration of hydraulic performance and wildlife passage in this research is driven by the overarching goal of achieving cost-effectiveness in transportation infrastructure. By combining these two elements, we aim to optimize the allocation of transportation funds, allowing them to have a greater impact on improving our road networks, preserving our environment, and protecting wildlife.

This research will not only provide practical solutions to mitigate the negative impacts of culvert design on wildlife but will also help create more efficient and sustainable transportation systems. By doing so, we can simultaneously improve road safety and preserve Georgia's unique biodiversity, ultimately ensuring that every transportation dollar has the greatest impact.

The objectives of Phase I are to:

- Perform a preliminary literature review of best practices (including floodplain relief culverts, staged barrels, shelving, and vegetation / non-fencing directive techniques) for integrating hydraulic design with wildlife passage for reduced WVCs in different GA regions.
- Based on the preliminary literature review, provide GDOT with a brief prospectus on the potential use of practices that have the highest likelihood of both reducing WVCs and improving safe flood conveyance.
- Develop a Phase II research project scope for GDOT with the details of a research project and with potential objectives, including but not limited to:
- detailed guidance on the use of practices and culvert designs that have the highest likelihood of reducing WVCs and safely passing floods and debris in a changing operating environment (increasing rainfall intensity) as appropriate for different regions of GA.
- a review of the culvert design standards in the context of climate change.
- practical approaches to combining hydraulic design methods with techniques for reducing the likelihood of WVCs (this includes case studies and HEC-RAS modeling).
- a spatial prioritization and decision support toolbox for targeting resources

from the Infrastructure Investment and Jobs Act and other sources to both reduce WVCs and improve hydraulic performance.

- recommendations for the GDOT's Drainage Design for Highways manual, including guidance on where (and for which taxonomic groups) various features of vegetation management strategies are appropriate and when they are inappropriate because of debris, flow intensity, inundation, and biological considerations; and a workshop for DOT on practical approaches to combining hydraulic design methods for sediment and debris conveyance, organism passage, and innovative techniques for reducing the likelihood of WVCs (including case studies).

SIGNIFICANCE OF RESEARCH

The benefits of this project will include reduced WVCs, reduced permitting times, improved climate resiliency for bridges and culverts, and lower maintenance costs because features that facilitate the safe passage of wildlife can, in many instances, also facilitate the safe passage of floods and debris. Safe passage of wildlife and floods ultimately promotes public safety and reduces costs.

REPORT STRUCTURE

In the pursuit of safer roads, enhanced ecological connectivity, and improved wildlife conservation in the state of Georgia, this technical report explores the potential for integrating hydraulic design with wildlife passages. In Chapter 2, we explore our systematic literature review process and methodologies, designed to identify best practices for integrating hydraulic design with wildlife passages to reduce WVCs in Georgia.

In Chapter 3, we present promising strategies for reducing WVCs while improving safe flood conveyance, including multiuse underpasses and modified culverts.

Finally, in Chapter 4, based on what we found in the literature review, we develop the scope of Phase II, which aims to create a systematic approach for evaluating ecological and structural variables to enhance hydraulic performance, reduce WVCs, ensure safe wildlife passage, and bolster infrastructure resilience. A full draft of the Phase II proposal is included in Appendix II. Finally, information about accessing the full database of literature is included in Appendix III.

As detailed throughout this document and rooted in our preliminary literature review, we have identified core ecological factors that are firmly established. These underscore the necessity for structural designs tailored to specific contexts in order to simultaneously attain objectives such as road safety, ecological sustainability, and the protection of wildlife in Georgia. Notably, our preliminary findings suggest that multi-use underpasses and culverts hold substantial promise. These structures have the potential to significantly enhance wildlife crossings, reduce Wildlife Vehicle Collisions (WVC), improve transportation safety, foster ecosystem connectivity, and facilitate the conveyance of water and debris.

CHAPTER 2. PRELIMINARY LITERATURE REVIEW

METHODOLOGY

We conducted a systematic literature search and preliminary review (Foo et al. 2021) to identify the best practices for integrating hydraulic design with wildlife passage to reduce Wildlife Vehicle Collisions (WVC) in Georgia. A review protocol was iteratively written, piloted, and revised with the assistance of UGA Science Librarian's Stephanie Blair and Diana Hartle. The protocol outlines and documents inclusion and exclusion terms (as shown in Figure 1), literature sources, search strings, their development, and the screening process (see Appendix I). Relevant papers were categorized by date, locality, species groups, structure(s), and structural specifications for subsequent synthesis.

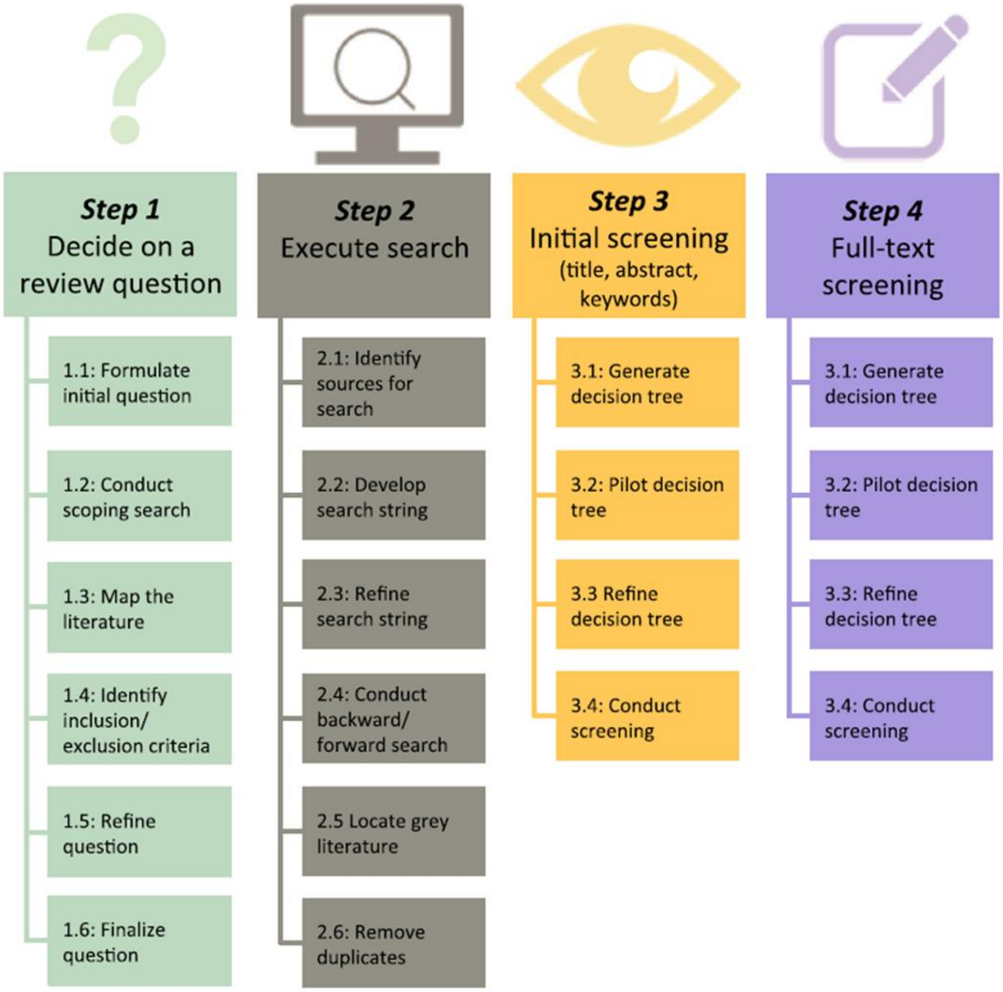

Figure 1. Methods used to systematically search, screen, and synthesize literature for phase I (Foo et al. 2021)

Literature search

For this review we searched both primary and secondary literature sources. These sources included Web of Science (all databases and all collections), and ProQuest (Agriculture & Environmental Science Collection, Dissertations & Theses at the University of Georgia, ProQuest Dissertations & Theses Global, and the Biological Science Collection). Preliminary searches utilized Google Scholar; the database was ultimately excluded from the final search protocol, but papers identified as relevant during this preliminary step were included.

Search terms targeted relevant hydraulic structures, wildlife-roadway interactions, and crossing structures. Hydraulic structures were limited to abstracts or titles to focus search results.

culvert OR bridge* OR underpass* OR "floodplain relief" OR "stream crossing*" OR "perched crossing*" OR "drainage structure*" AND roadkill OR "road ecology" OR "road mortalit*" OR "animal-vehicle collision*" OR "wildlife-vehicle collision*" AND "wildlife passage " OR "animal passage" OR "wildlife crossing" OR "animal crossing*" OR "road use" OR "road mitigation*"*

Because state transportation departments are key contributors to this body of knowledge, snowball sampling was employed to complement secondary literature sources. This is a recruitment technique traditionally used in the social and medical sciences to identify research subjects (Parker, Scott, and Geddes 2019). Research participants are asked to assist researchers in identifying other potential participants. Within the context of our review, experts and practitioners were asked to share relevant papers and to pass along our request to other relevant individuals. Search results were also complemented with the references from two Georgia DOT funded projects carried out by students at Emory University.

Inclusion and exclusion criteria

We used decision trees during the screening processes to apply inclusion and exclusion criteria (see Appendix I). A paper was included if it was published or reported after 2002 and evaluated wildlife use of hydraulic structures or contained information about structural design specifications that facilitate wildlife movement and could be applied to hydraulic structures. There was no restriction on locality, species, or hydraulic structure. We did not exclude previously unpublished authors from our collection of conference papers, theses, or dissertations. Because reviewers were not multilingual, only studies published in English were included. Duplicate studies were removed before screening and upon the convergence of iterative search results. Citation based searches (backward and forward searches) were conducted for literature reviews and other papers published or reported after 2013 that were identified during the screening and early synthesis as central to the body of knowledge.

RESULTS

All searches collectively returned 757 papers of which 253 and 291 we discarded during preliminary and full-text screening respectively, producing 213 relevant papers. These were screened by reading select sections and categorizing and summarizing relevant information; however, given the time and resources allocated to this phase of the project, the papers were not read entirely nor critiqued for methodological or inferential rigor. During the reading phase, an additional 36 papers were removed because they contained adjacent but not directly applicable information. Two of these papers were used for citation-based searches but were not used directly in our review. This resulted in 177 papers that contained information we believed would help us identify the ecological and structural variables that best facilitate wildlife passage through hydraulic structures and reduce WVC.

Of the 177 papers used in this review 104 were peer reviewed journal articles, 48 were state or federal reports, 19 were conference papers, theses, or dissertations, and 6 were books or book chapters. During the synthesis process we summarized supported practices and identified the types of structures and species groups analyzed. Seventy papers discussed a diversity of crossing structures; 41 focused exclusively on culverts and pipes; 63 focused on underpasses, bridges, and other larger structures; and 2 presented a novel crossing structure design. Those that explored a variety of crossing structure types often evaluated a broad suit of wildlife. The papers that focused on smaller structures almost exclusively evaluated their use by herpetofauna or small mammals. Those that focused on larger structures most often evaluated their use by larger mammals. Medium sized mammals were often discussed alongside larger mammals but were sometimes compared to smaller species using smaller structures. Approximately 29% of the papers focused exclusively on herpetofauna or small mammals, 32% focused on large mammals, and 36% focused broadly on wildlife in the focal area. Three percent of the papers (5 papers) on the passage of aquatic organisms like fish and stream-dwelling salamanders were included.

Hydraulic structures were often described and evaluated in terms of length, width, height, sky exposure, substrate; dry path, ledge, or bench; line-of-sight, cover, adjacent vegetation, and fencing. We used these attributes to further group the practices supported by each paper and to discuss best practices in our synthesis below. Fencing has its own suite of ecologically and structurally important variables that were not used to categorize papers during screening or early synthesis, but we did use them to discuss best practices in our synthesis. They include fencing material, extent, height, end treatment, and top/bottom modifications.

DISCUSSION

The core ecological variables associated with the facilitation of wildlife passage and the reduction of WVC are well understood and have been robustly supported over the last two decades. The findings and recommendations of papers from the early 2000s (Forman 2003; Smith 2003a; Jochimsen et al. 2004; Cramer and Bissonette 2005) remain well supported by more recent papers that we identified as foundational to current best practices (Huijser et al. 2016; Gunson et al. 2016; Ford and Clevenger 2019; Ford, Huijser, and Clevenger 2022; Ford et al. 2022; Huijser and Begley 2022a; . The last decade of study has not altered the state of this core knowledge but has empirically supported what was merely expert opinion. With the growth in empirical studies, there is more nuanced understanding of how specific taxa or approaches may affect wildlife passage or reduce WVCs. These nuances allow us to better consider how we can and cannot prescribe the facilitation of wildlife passage and the reduction of WVCs. The nuance and context of the growing number of studies do demonstrate that designing or modifying a structure to facilitate the passage of wildlife and reduce WVC can be relatively unique to each combination of structure, hydrology, species, and landscape context. As a result, best practices can also be perceived as unique to each context, prohibiting the prescriptive defining of structural variables. We have attempted to synthesize current best practices into broad guidelines (e.g., maintain natural sky exposure) to provide flexibility depending on context (e.g., target taxa, habitat type).

The state of knowledge surrounding structural variables has not advanced in this vein. It is the opinion of the reviewers that this is likely due to practical restrictions on scale and scope. Researchers and state DOTs alike have not had the funds or logistical capacity to install the diversity of structures in the variety of habitats that would be required for what would be considered a robust study design. However, we would note that adaptive management frameworks that include built in predictions and learning mechanisms linked to modeling could develop the needed knowledge within the normal operating processes of many DOTs if there was a commitment to such learning (Lyons et al. 2008; Allen et al. 2011; Rehme, Powell, and Allen 2011; Williams and Brown 2018). Those studies that did incorporate classic research designs often did so at small scales that made it difficult to scale up to realistic scenarios (Woltz, Gibbs, and Ducey 2008; Sievert and Yorks 2015).

Hydraulic structures designed or modified to facilitate the passage of wildlife do reduce wildlife vehicle collisions if properly designed and maintained. We have summarized recommended best practices in Table 1. Here we synthesize those recommendations while representing the sources that support our recommendations. In general, hydraulic structures designed or modified to facilitate the passage of wildlife should be constructed and augmented in a way that maximally emulates the habitat and spaces through which target species move. When possible, passages should minimize length, particularly when incorporation of more natural substrates, sky exposure, or vegetation is limited (Smith 2003b; Clevenger 2005; Dodd et al. 2007a; Dodd et al. 2007b; Donaldson 2007; Seiler and Olsson 2009; Sawyer, Lebeau, and Hart 2012; Cramer 2013; Hopkins, Harman, and Kuchta 2019; Bhardwaj, Olsson, and Seiler 2020; Rivera 2020; Santoro et al. 2023; Denneboom, Bar-Massada, and Shwartz 2021). Structures should *maximize width and height or – at a minimum - align the width and height to meet the spaces through which target species will move* (Smith 2003b; Clevenger 2005; Dodd et al. 2007a; Dodd et al. 2007b; Donaldson 2007; Seiler and Olsson 2009; Sawyer, Lebeau, and Hart 2012; Cramer 2013; Hopkins, Harman, and Kuchta 2019; Bhardwaj, Olsson, and Seiler 2020; Rivera 2020; Santoro et al. 2023; Denneboom, Bar-Massada, and Shwartz 2021; Cramer 2019; Cramer and Hamlin 2017; Wang et al. 2018)**.** Structures should maximize natural sky exposure to allow ambient moisture, light, and temperature to enter the structure (Jochimsen et al. 2004; Woltz, Gibbs, and Ducey 2008; Sievert and Yorks 2015; Hopkins, Harman, and Kuchta 2019; Santoro et al. 2023; Bissonette and Cramer 2008; Colley et al. 2017; Clevenger and Huijser 2011; Beebee 2013; Baxter-Gilbert et al. 2015; Ontario Ministry of Natural Resources and Forestry 2016; Pomezanski and Bennett 2018; Markle and Stapleton 2022; Donaldson 2022), have natural substrates (Forman et al. 2003; Jochimsen et al. 2004; Smith 2003b; Gunson et al. Clevenger and Huijser 2011; Beebee 2013; Pomezanski and Bennett 2018; Donaldson 2022; Glista, DeVault, and DeWoody 2009; Lesbarrères, Lodé, and Merilä 2004; Kautz, Bittner, and Logan 2010) *including cover objects* Bissonette and Cramer 2008; Clevenger and Huijser 2011; McDonald and St. Clair 2004; Connolly-Newman et al. 2013; D'Amico et al. 2015; Smith, van der Ree, and Rosell 2015; Grilo, Bissonette, and Santos-reis 2008; Saxena and Habib 2022), have a 3m wide dry path, ledge, or bench along either side of a water body (Forman et al. 2003; Clevenger and Huijser 2011; Donaldson 2022; Bissonette and Cramer 2008; Clevenger and Ford 2010; Villalva et al. 2013, and *have vegetation that is continuous and homogeneous with the adjacent habitat or the habitat preferences of the target species* Ford, Huijser, and Clevenger 2022; Clevenger and Huijser 2011; Glista, DeVault, and DeWoody 2009; . The presence of vegetation at the entrance and within the structure is of particular importance for structures that connect lotic waterbodies. Species adapted to move along these waters may be reluctant to enter the structure if lotic vegetation is absent (Clevenger and Huijser 2011; Clevenger and Waltho 2003). A number of publications recommend limiting human activity or passage within structures and that designs include a means to minimize traffic or other significant, human-caused noise, which in some cases could also be accomplished with vegetation around structures (Forman et al. 2003 Clevenger and Huijser 2011; Grilo, Bissonette, and Santos-reis 2008; Denneboom, Bar-Massada, and Shwartz 2021; Bissonette and Rosa 2012; Bissonette and Cramer 2008; .

A substantial number of studies demonstrate that structures to facilitate wildlife passage only work or work better to reduce WVC when they include carefully designed and well-maintained fencing (Ford et al. 2022; Dodd, Gagnon, Boe, et al. 2007; Dodd, Gagnon, Manzo, et al. 2007; Denneboom, Bar-Massada, and Shwartz 2021; Cramer and Hamlin 2017; Bissonette and Cramer 2008; Clevenger and Huijser 2011; Donaldson 2022; Bissonette and Rosa 2012; Cunnington et al. 2014 Donaldson, Kweon, and Lloyd 2015; Gagnon et al. 2015 Donaldson and Elliott 2020; Ferenchak 2020; Cramer and Hamlin 2021; Donaldson and Elliott 2021; . *Effective fences extend parallel to the road and well* *beyond crossing structures, preferred habitat for target species, and roadkill hotspots* Hopkins, Harman, and Kuchta 2019. *Effective fences also have ends that are bent in towards a crossing structure or are otherwise designed to deter wildlife from continuing beyond or around the end of the fence* (Hopkins, Harman, and Kuchta 2019; Ferenchak 2020; Cramer and Hamlin 2021; Helldin and Petrovan 2019; . *Fences must be tall enough to prevent target wildlife from climbing or jumping over, and must be buried to prevent wildlife from digging under the fence* Clevenger and Huijser 2011; Beebee 2013; Goldingay et al. 2022; Gagnon et al. 2016 Bager and Fontoura 2013; . *Guidelines for small mammals and herpetofauna recommend a height of 2.0 - 7.0 ft (0.6 – 2.0 meters) and buried to a depth of 2 – 4 inch (5 – 10 cm). Guidelines for medium and large bodied mammals recommend 10ft (3 m) tall fencing buried 3.6 ft (1.1 m) deep.* Fencing materials and designs must account for the size, behaviors, climbing, jumping, and burrowing capabilities of wildlife to be effective in preventing wildlife from passing over or through the fence and to prevent wildlife from becoming trapped in the fencing material Ferenchak 2020; Baker 2022; Gordon and Anderson 2003; ; Hooker et al. 2016). Fences with an overhanging lip to top that bends away towards the presumed path of wildlife can be used to target species that might climb over shorter fencing (; Clevenger and Huijser 2011; Beebee 2013).

Modification of structure length, height, or width may be appropriate depending on target species. Species that prefer more open, low canopy habitats are more likely to use structures that are more open by maximizing width and height (Murphy-Mariscal, Barrows, and Allen 2015; Clevenger and Waltho 2005; Donaldson 2007), whereas species that are adapted to closed canopy habitat or take refuge within structurally complex or subterranean habitats may prefer or better tolerate structures that are narrower (Woltz, Gibbs, and Ducey 2008; Clevenger 2005; Hopkins, Harman, and Kuchta 2019; Beebee 2013; Murphy-Mariscal, Barrows, and Allen 2015; Colley 2017a; Chen, Posthumus, and Koprowski 2021). Studies show that larger mammals consistently prefer small bridges and underpasses over culverts (Ford, Huijser, and Clevenger 2022; Wang et al. 2018; Mata et al. 2003; Mata et al. 2005; Andis, Huijser, and Broberg 2017; Sugiarto 2023), whereas small mammals, amphibians and reptiles often preferred culverts (Kautz, Bittner, and Logan 2010; Ruediger and DiGiorgio 2007; Mata et al. 2005). Structures that are designed to meet the needs of a diversity of species are recommended to meet the dimensional needs of large animals adapted to open spaces but provide internal structural complexity and cover for other species. Overall medium-to-large box culverts with natural substrate were the preferred culvert design to accommodate most species (Ford, Huijser, and Clevenger 2022; Jackson, Smith, and Gunson 2015; Kautz, Bittner, and Logan 2010; Ruediger and DiGiorgio 2007; Mohammadi et al. 2018). Ruediger and DiGiorgio (2007) suggested this may be due to the larger interior space and openness of box culverts compared to round culverts of similar size. Many studies have stressed the value of creating a diversity of crossing structure types and size classes along a roadway to facilitate the passage of different wildlife (Ford, Huijser, and Clevenger 2022; Clevenger 2005; Rivera 2020; Saxena and Habib 2022; Martinig and Bélanger-Smith 2016; Murphy-Mariscal, Barrows, and Allen 2015; Denneboom, Bar-Massada, and Shwartz 2021; Lala et al. 2022; Mata et al. 2005; Mata et al. 2003; Ford, Barrueto, and Clevenger 2017; Schroder and Sato 2017; Peaden et al. 2017; González-Gallina, Hidalgo-Mihart, and Castelazo-Calva 2018; Mohammadi et al. 2018).

Spacing of wildlife crossing structures is another important decision stressed by numerous sources Dodd et al. 2007a; Dodd et al. 2007b; Bhardwaj, Olsson, and Seiler 2020; Clevenger and Huijser 2011; Mouta 2020; Clevenger and Waltho 2003; Klar, Herrmann, and Kramer-Schadt 2009; Huijser, Gunson, and Fairbank 2017; Cramer and Hamlin 2021; Ottburg and van der Grift 2019; Gordon and Anderson 2003; Crook, Cairns, and Vernes 2013). The literature supports placing passages frequently along a roadway (Bhardwaj, Olsson, and Seiler 2020; Clevenger and Waltho 2003; Klar, Herrmann, and Kramer-Schadt 2009; Cramer and Hamlin 2021). For example, a study of migrating California tiger salamanders (*Ambystoma californiensis*) found that fenced crossing structures spaced every 41 ft (12.5 meters) best facilitated successful passage . Culverts designed to facilitate the crossing of small mammals may be most effective when placed every 500-1000 ft (150-300 meters) along the roadway (Clevenger, Chruszczc, and Gunson 2003), whereas for larger mammals, one fenced culvert every 2650 - 3610 ft (800 – 1100 meters) may be sufficient (Dodd et al. 2007b; Donaldson 2022). When deciding on the spacing of crossing structures, considering the average daily movement of species of interest may provide a good starting point for decision-making (Serronha et al. 2013).

Context and Caveats

Many reports identified through our literature review mirror the requests and knowledge gaps identified by the research proposal that initiated this literature review (Bissonette and Cramer 2008; Kintsch and Cramer 2011; Cramer 2022). This redundancy highlights the desire among many transportation departments for prescriptive solutions and the challenges in identifying clear solutions. Our review is accurately identified as a preliminary literature review. No metanalysis was conducted; therefore, the information should be understood and applied as recommendations from the reviewers. Because of the volume of papers, we could not evaluate the veracity or rigor of the methods, inferences, and associated recommendations. Conclusions and recommendations were taken at face value. Critical evaluation and weighting of studies would require a thorough, critical read of all papers. This could be incorporated into a future project phase.

There may be complexities or different levels of support for the attributes described in the synthesis that we do not discuss. If a more critical evaluation of specifications is of interest, the full text of these papers will need to be thoroughly read and synthesized and could also be incorporated into a future project phase.

SUMMARY OF FINDINGS

Based on the results and discussion presented above, we summarize in Table 1 and Table 2 best practice recommendations for the group of species in which the review sources include them.

Table 1. Attributes of hydraulic structures that facilitate connectivity along aquatic habitats (wetlands, ponds, lakes, streams, or rivers) or between aquatic and terrestrial habitats.

Species Group	Best Practices
Medium to Large Mammals	• Best structure dimensions and attributes will depend on target species. **Consider structures that can accommodate multiple species** by including attributes for smaller species within larger, more open structures. o Species adapted to open spaces likely prefer more open. o Species that take refuge within structurally complex habitats may be more likely to use narrower structures. • **Include fenced medians** for structures crossing multiple roadways (e.g., divided highways). • **Maximize natural sky exposure** by incorporating open-top design features like slots or open grates. • **Maintain natural substrate** by using an open bottom, placing natural substrate in the structure, or burying the bottom (open bottom structures best facilitate the passage of wildlife). • **Include 3 – 10 ft (1-3-meter)-wide dry paths** or ledges that maintain a clear line of sight along each side of water body or through rip rap. Paths / ledges should remain dry under all but the most annual high flow. • **Include vegetation at the entrance** and within the structure (type and dimensions of vegetation will depend on target wildlife and could match natural vegetation in area). • **Minimize noise** (e.g., vehicular traffic) by maintaining vegetation near the entrance. ▪ **Restrict human passage.**

Herpetofauna and Small Mammals	• **Length < 82 ft (25m)** [can be shortened by installing headwalls and varying width]. • **Include fenced medians** for structures crossing multiple roadways (e.g., divided highways). • **Maximize natural sky exposure** by incorporating open-top design features like slots or open grates. • **Maintain natural substrate** by using an open bottom, placing natural substrate in the structure, or burying the bottom (open bottom structures best facilitate the passage of wildlife). • **Include 3 – 10 ft (1-3-meter)-wide dry paths** or ledges that maintain a clear line of sight along each side of water body or through rip rap. Paths / ledges should remain dry under all but the most extreme flow events. • **Include cover objects** such as flat rocks or woody debris that do not obstruct the dry path or line-of-sight. • Consider inclusion of railings or logs that extend beyond the entrance to the structure to facilitate passage of scansorial and arboreal species. • Include vegetation at the entrance and within the structure (type and dimensions of vegetation will depend on target wildlife and could match natural vegetation in area). • **Minimize noise** (e.g., vehicular traffic) by maintaining vegetation near the entrance. • **Restrict human passage**. • Many herpetofauna migrate "perpendicular" [not parallel] to water bodies to access higher terrestrial habitats that do not flood and are critical to their life cycle. Structures using the attributes above but oriented along key migration paths between aquatic and terrestrial habitats may be needed to reduce wildlife vehicle collisions for these taxa. • Passage and presence of bats should be carefully managed to reduce the buildup of guano along dry paths.

Table 2. Attributes of fencing associated with hydrologic structures to facilitate wildlife connectivity.

Species Group	Best Practices
Medium to Large Bodied Mammals	• **Fencing should extend at least the entire length of target habitat but ideally 5 km beyond target habitat**. • **Include jump outs for deer**. • **Curve the end of the fencing towards a crossing structure** (45°-90° degree angle or a u-shaped turn). • For deer, consider embedding round wildlife guards into the roadway. • For deer and bears, consider plant trees and dense vegetation as a fencing extension. • **Use a durable wire mesh or chain-link material**. • Include finer gauge fencing along the bottom of fence to exclude herpetofauna and small mammals from passing through into areas of concentrated use by larger mammals (see attributes above). • **Use 10 ft (3 m) tall fencing** for broadest suite of large mammals. • **Bury fencing 3.6 ft (1.1 m) deep**.
Herpetofauna and Small Mammals	• **Fencing should extend at least the entire length of target habitat but ideally 330 ft (100 m) beyond target habitat**. • For herpetofauna migrating to terrestrial habitats, **limit distances between crossing structures to 150 ft (45m)** and **crossing structures should be the highest points on the landscape**. • **Curve the end of the fencing towards a crossing structure** (45°-90° degree angle or a u-shaped turn). • Use a smooth, solid fencing material. If wire mesh is used it is critical that the gauge be no larger than ¼ inch to prevent entrapment. • **Use 2.0 - 7.0 ft (0.6 – 2.0 m) tall fencing** for broadest suite of herpetofauna and small mammals. A fence < 3 ft (1 m) tall will not exclude medium to large snakes. Short fences may be mitigated with an overhanging lip bent away from the road to prevent species capable of climbing or jumping from moving over the fence. • **Bury fencing 2 – 4 inch (5 cm – 10 cm) deep**.

CHAPTER 3. PROSPECTUS FOR REDUCING WVCS AND ENHANCING SAFE FLOOD CONVEYANCE

In this section, we present a brief prospectus based on our preliminary literature review regarding the potential utilization of practices that offer the greatest promise in simultaneously reducing Wildlife-Vehicle Conflicts (WVCs) and enhancing safe flood conveyance. In general, we can state with confidence that the findings of this Phase I project indicate that the Phase II project described below has a high likelihood of successfully achieving the proposed objects for enhancing road safety through multi-purpose culvert design. First, there is sufficient knowledge to move forward with developing design guidelines for triple-win culverts (better convey floods, reduce WVCs, and improve aquatic connectivity). Second, there are hotspots where all three issues co-occur: undersized for flood conveyance, high incidence of WVCs, and lack of aquatic connectivity where case studies and pilot projects could demonstrate the feasibility and benefits of multi-purpose design. Third, design modifications for flood and sediment conveyance under climate change are in accordance with modifications that reduce WVCs, reduce maintenance costs, and promote aquatic connectivity to improve road safety. A phase II project will produce a level of design guidance for GA on par with western US and integrate guidance for climate robust culvert designs that simultaneously reduce WVCs and provide aquatic organisms passage.

REDUCING BARRIER EFFECT TO IMPROVE WILDLIFE CROSSING

As outlined in the European Handbook for Managing Wildlife and Traffic Conflicts (Iuell 2003), selecting the right wildlife passage depends on factors like the landscape, affected habitats, and species' needs. In this context, multiuse underpasses stand out as a highly suitable option for establishing secure crossing points that cater to a diverse array of wildlife, as depicted in Figure 3.

Multiuse underpasses are integrated into transport infrastructure, serving both wildlife and humans, like forestry roads, paths, and cattle crossings. These structures can be improved for wildlife with features like fencing, vegetation adjustments, and measures against water pooling. When needed, fencing and noise-reduction screens guide animals and reduce traffic disturbances.

Figure 3 also depicts modified pipe or box culverts, allowing water flow and aiding aquatic and terrestrial wildlife crossing. They often have dry ledges connecting to nearby habitats. Various studies (Brunen, Jaeger, Jochen 2020; Marangelo 2019; Donaldson 2022; Warnock-Juteau et al. 2022) highlight the potential to enhance drainage culverts as wildlife passages, especially in a changing climate with more intense storms. These studies emphasize the link between structure design and wildlife movement, examining factors like culvert material, water depth, lunar brightness, and environmental variables. Comprehensive assessments are vital for success.

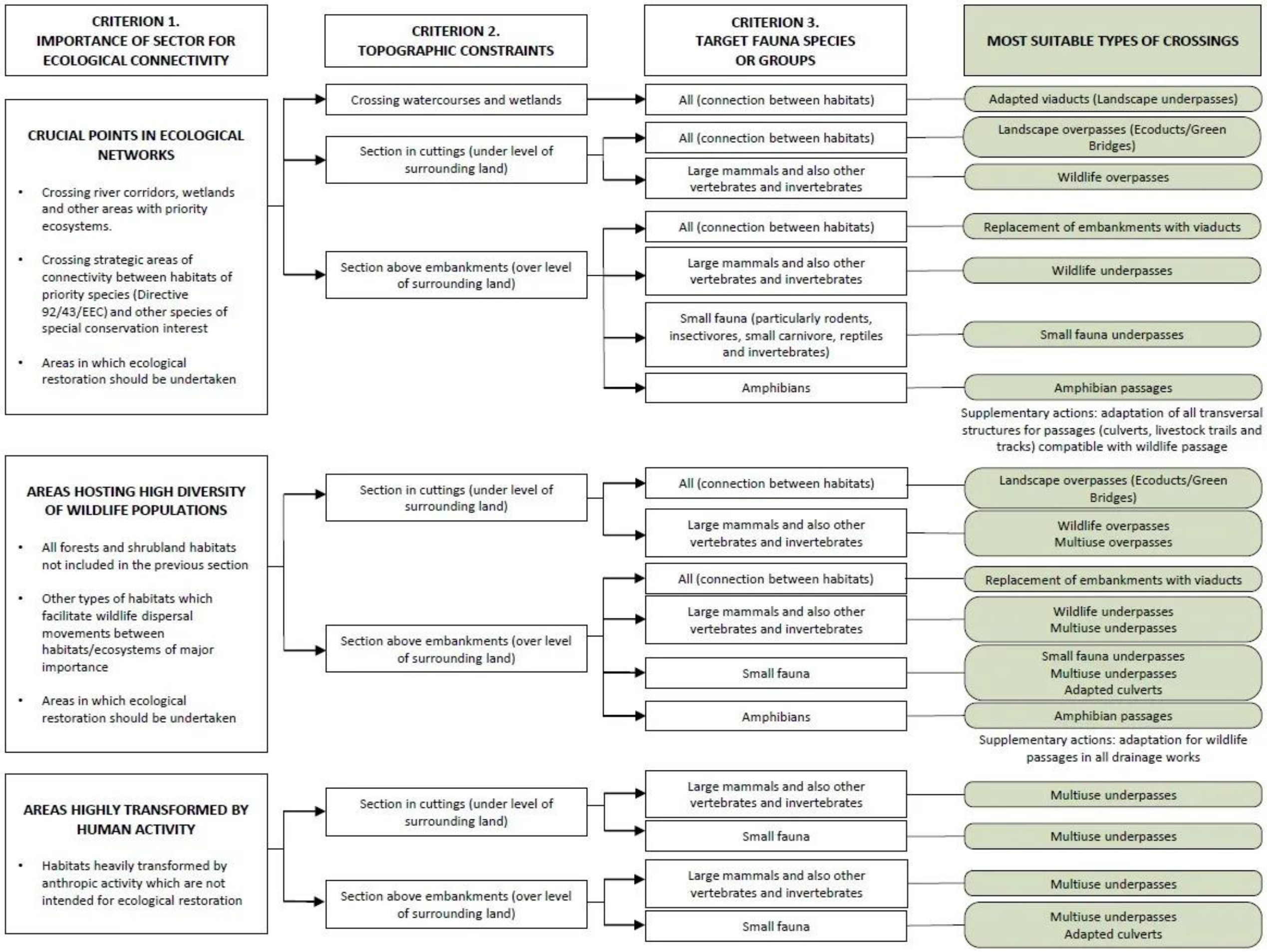

Figure 2. Example of the decision criteria processes involved in the selection of the most suitable wildlife crossing type based on factors such as ecological connectivity, topographic constrains, and target species (Iuell 2003).

BEST PRACTICES AND HYDRAULIC STRUCTURES

Drawing from the best practices outlined in Tables 1 and 2, we have formulated a preliminary classification system based on the water conveyance capacity of hydraulic structures and their design approach. This classification (Table 3) as a first step towards simultaneously achieving multiple objectives, is based on the perceived suitability of these best practices for each type of hydraulic structure, accounting for their specific design and function, complemented with the literature review findings.

Suggested Best Practice	Hydraulic Structure Type					
	Culverts					Bridges underpasses
	Open bottom or arch-span culverts	Culvert batteries	Floodplain culverts	Round/circular culverts/pipes	Box culverts and pipe arch culverts	
Fences						
Headwalls						
Decreasing structure length						
Width and height modification						
Open top structures (slots or open grates set on concrete footings)						
Natural substrate						
Dry paths or ledges						
Dry ledges or benches						
Target species width and height adaptation						
Internal structural complexity and cover						
Substrates in concrete blocks, rocks, logs or other woody debris*						
Rocks or woody debris cover						
Vegetated entrance to minimize noise*						
Vegetated entrance*						
Wood or log railings extending beyond the entrance of the						

Suggested Best Practice	Hydraulic Structure Type					
	Culverts					Bridges underpasses
	Open bottom or arch-span culverts	Culvert batteries	Floodplain culverts	Round/circular culverts/pipes	Box culverts and pipe arch culverts	
structure*						
Vegetation within the structure*						
Exclude human activity						

Blue = Suitable
Yellow = Generally not appropriate
* Only if compatible with hydraulic conveyance and maintenance objectives

Table 3. Compatibility of Hydraulic Structure Types with Multiple Objectives

From the table above, certain best practices can be broadly applied to various culvert and underpass types to enhance their effectiveness in mitigating wildlife-vehicle collisions and promoting ecosystem connectivity. These include practices like excluding human activity, incorporating vegetated entrances to minimize noise disturbance, providing dry paths or ledges, and strategically placing rocks or woody debris covers. These elements help create inviting passages for wildlife. Additionally, implementing wood or log railings that extend beyond the entrance of the structure can offer guidance and safety to animals during their crossings. Such measures can help align these diverse structures with the overarching goals of reducing wildlife-vehicle collisions and fostering habitat connectivity. However, in determining the applicability of identified best practices to bridges and culverts, it's crucial to consider the specific characteristics and ecological contexts of each structure type.

Additionally, with strong evidence from our initial literature review, reinforced by the State Infrastructure Report Card's (American Society of Civil Engineers 2022) urgent call for resilient infrastructure in the face of climate change, and the identification of problem areas in Georgia where flooding, WVC, and aquatic ecosystem barriers converge, Phase II of our project becomes a clear necessity.

CHAPTER 4. PHASE II RESEARCH PROJECT

Building on the findings of Phase I, the Phase II research project aims to provide the Georgia Department of Transportation (GDOT) with a comprehensive scope that addresses the complex challenges of reducing Wildlife-Vehicle Conflicts (WVCs) while ensuring safe flood conveyance and ecological connectivity. This scope outlines potential objectives and research areas to guide Phase II.

The general scope of activities included in the Phase II project proposal (**see Appendix II for a detailed draft of the Phase II proposal)** is as follows:

Task 1: Design standards and previous lit-review wrap-up

This task involves organizing a workshop to develop hydraulic design standards, focusing on culvert designs that effectively reduce WVCs and safely accommodate changing environmental conditions, such as increasing rainfall intensity across various regions of Georgia. Additionally, it includes an in-depth literature review to extract context-specific recommendations for minimizing barrier effects and enhancing wildlife crossings, with a special emphasis on culverts and multiuse underpasses.

Task 2: Culvert Design Standards in the Context of Climate Change

This task centers on reviewing existing culvert design standards within the context of climate change. Its goal is to establish a framework that integrates hydraulic design techniques with innovative approaches for WVC reduction. This integration aims to identify opportunities where hydraulic performance and strategies for reducing WVCs can synergize, building upon the insights gained from Task 1 and Phase I.

Task 3: Spatial Prioritization and Decision Support Toolbox

Task 3 involves creating a spatial prioritization framework and a decision support toolbox. These tools will guide the allocation of resources, including those from the Infrastructure Investment and Jobs Act, to target areas for intervention. The prioritization criteria will consider the dual objectives of reducing WVCs and enhancing hydraulic performance. Decision-making tools will consider ecological, safety, and infrastructure factors.

Task 4: Integrating Hydraulic Design and WVC Reduction

This task encompasses the design of case studies and HEC-RAS modeling for a selected area. Here, the focus is on applying geomorphic simulations as a culvert design method to simultaneously achieve multiple goals. These objectives include reducing wildlife-vehicle collisions, enhancing ecosystem connectivity, efficiently conveying water and debris to prevent flooding, prioritizing road safety, and potentially optimizing resource allocation for maintenance and replacement investments.

Task 5: Recommendations for GDOT Hydraulic Design Manual

Task 5 aims to provide recommendations for enhancing the GDOT hydraulic design manual. These recommendations will include guidance on the suitability of various vegetation management strategies for different taxonomic groups. The task will also address scenarios where specific strategies might be unsuitable due to factors like debris, flow intensity, inundation, and biological considerations. Additionally, it will involve a workshop for GDOT to explore practical approaches for combining hydraulic design methods and innovative techniques for WVC reduction, supported by real-world case studies.

Task 6: Training on Practical Approaches

The final task involves organizing a workshop for GDOT, focusing on practical approaches to integrate hydraulic design methods for sediment and debris conveyance, organism passage, and innovative WVC reduction techniques. The workshop will include real-world case studies to illustrate successful implementation and promote knowledge exchange and collaborative problem-solving among experts and stakeholders.

In summary, the Phase II research project scope presented here encompasses a multifaceted approach to address the complex challenges posed by WVCs, climate change, and hydraulic performance. These objectives collectively aim to provide GDOT with the tools, knowledge, and guidance needed to make informed decisions and enhance transportation infrastructure while promoting ecological sustainability and road safety.

CHAPTER 5. CONCLUSIONS

This preliminary literature review on wildlife passages and their role in mitigating Wildlife Vehicle Collisions (WVCs) and enhancing ecological connectivity reveals several key insights. First, fundamental ecological variables for effective wildlife passage design have remained consistent for the past two decades. These principles encompass emulating natural habitats, minimizing passage length when feasible, optimizing dimensions, ensuring exposure to the natural sky, utilizing natural substrates and cover objects, and maintaining continuous vegetation. This consistency underscores the vital role of these ecological factors in facilitating wildlife movement.

Secondly, the review emphasizes the context-specific nature of effective wildlife passages. The unique combination of structural, hydrological, species-related, and landscape factors necessitates a tailored approach. Consequently, the conventional concept of 'best practices' must be adaptable to each location's distinct circumstances. These findings provide a robust foundation for future research, highlighting the importance of context-specific studies to refine wildlife passage guidelines and contribute to safer roads and enhanced ecological connectivity.

As a result, we present a prospectus based on this preliminary literature review, outlining promising practices to reduce WVCs and enhance flood conveyance safety. We explore the suitability of multiuse underpasses as secure crossing points for wildlife and humans, emphasizing features such as fencing, vegetation adjustments, and noise reduction. Additionally, we recognize the potential of modified pipe or box culverts for facilitating aquatic and terrestrial wildlife crossings, considering factors like culvert material, water depth, and environmental variables.

In general, literature groups best practices for two main species groups identified (herpetofauna and small mammals and medium to large mammals), reveal essential design principles. To facilitate the safe movement of herpetofauna and small mammals, we recommend employing structures shorter than 82 ft (25 meters), which can be shortened with headwalls or variable widths, including fenced medians for multi-roadway crossings, maximizing natural sky exposure with open-top features, and maintaining natural substrate. Additionally, dry paths or ledges, cover objects, railings or logs, and strategically placed vegetation can enhance these passages, along with measures to minimize noise and restrict human passage. Recognizing that many herpetofauna migrate perpendicular to water bodies and managing bat passage to prevent guano buildup are crucial considerations. For medium to large mammals, tailoring structures to target species and their habitat preferences is vital. Fenced medians, open-top designs, natural substrates, dry paths or ledges, vegetation, noise reduction, and human restriction are also key recommendations. These findings provide valuable insights for developing wildlife passages that promote safety and ecological connectivity, aligning with our broader goal of resilient and sustainable infrastructure (for detailed recommendations, refer to the full proposal in the appendix).

This Phase I study lays the groundwork and bodes well for a comprehensive Phase II project that provides design recommendations for simultaneously achieving multiple objectives: reduced WVCs, safe flood and debris conveyance under climate change, and improved aquatic connectivity. Innovative designs that achieve all three objectives can increase safety, build climate resilience and reduces costs and maintenance requirements. As a result of this Phase I study, we conclude that there is sufficient knowledge to move forward with developing design guidelines for such multi-objective structures. It is also apparent that many of the design modifications for flood and sediment conveyance under climate change (e.g., increasing rainfall intensity) are in accordance with several modifications that also reduce WVCs and promote aquatic connectivity. Building upon these insights, Phase II of the project is poised to enhance road safety, ecosystem connectivity, and infrastructure resilience through development of hydraulic design standards, integration of climate change considerations, spatial prioritization if structure enhancements and replacements, and recommendations tailored for GDOT. By merging ecological knowledge with innovative engineering of wildlife friendly, climate-ready structures, this project aspires to forge a path toward safer and more sustainable transportation infrastructure in Georgia.

Supported by compelling evidence from our initial literature review, reinforced by the State Infrastructure Cards report's (American Society of Civil Engineers 2022) urgent call for resilient infrastructure in the face of climate change, and the identification of problem areas in Georgia where flooding, WVCs, and aquatic ecosystem barriers converge, Phase II of our project becomes an imperative. While Phase I lays out the opportunity, Phase II represents our path to specific solutions tailored for Georgia. It is evident that the time to act is now, as Phase II will crystallize our strategy for resilient and ecologically balanced infrastructure, ensuring safety and sustainability.

In this context, Chapter 4 outlines the scope of Phase II, which aims to develop a systematic approach integrating hydraulic, ecological, and structural variables. A full draft of the Phase II proposal is provided in Appendix II. This approach seeks to enhance hydraulic performance, bolster infrastructure resilience, reduce WVCs, and ensure safe wildlife passage simultaneously.

APPENDIX I. BRIDGE AND CULVERT DESIGNS FOR REDUCED WILDLIFE-VEHICLE CONFLICTS AND IMPROVED CLIMATE RESILIENCY

REVIEW DESIGN

Phase I: a preliminary literature review of best practices for integrating hydraulic design with wildlife passage for reduced WVCs in different GA regions. This document explicitly outlines the methods used to systematically search, screen, and synthesize literature for phase I. These methods are based on the recommendations of Foo et al., 2021 (see figure 1).

Question

Given the nature of this work, GDOT has formulated the initial and final question (steps 1.1 and 1.6): What are the best practices for integrating hydraulic design with wildlife passage to reduce WVCs in different GA regions?

Inclusion Terms + Scope

With the support of expert consultants (Gino D'Angelo and Brian Bledsoe) and preliminary work done by Alejandra Gomez we have conducted a scoping search, mapped the literature, and identified inclusion/exclusion criteria (steps 1.2, 1.3, and 1.4). Inclusion/exclusion criteria and terms were updated after the first iteration of steps 3 and 4. No additional terms were identified for exclusion; however, some terms were decidedly too broad. These terms have been crossed out. New terms specified during the first iteration of initial and full-text screening (piloting) are denoted with an asterisk. Because of the scope of this review, no terms were specified for exclusion.

- Scope:
  - spatially unlimited

- taxonomically unlimited
- hydraulic structures and practices are limited to those that are water adjacent.

Table 4. Inclusion Terms Grouped By Major Categories

Hydraulic Structures	Interactions	Practices	Objectives
culvert	roadkill	vegetation directive techniques	climate resilience
floodplain relief culvert	road/roadkill mitigation	non-fencing directive techniques	habitat connectivity
stream crossing	road ecology	shelving	wildlife/animal crossing*
perched crossing	road mortality	staged barrel	wildlife/animal passage*
drainage structure	animal-vehicle collisions	vegetation buffer*	road use*
bridge	wildlife-vehicle collisions	substrate*	
underpass	roadkill mitigation	opening*	
~~transportation~~	aquatic barrier	slope*	
~~surface transportation~~	collision risk*	dimensions*	
	hot-spot-road*		

Literature Sources

Literature sources were selected based on the recommendations of Gusenbauer et al., 2019 (2.1). Primary sources were selected to target prominent peer-reviewed literature. Supplementary sources were selected to target state, federal and non-governmental reports (2.5). ProQuest was added to supplementary sources after an initial iteration of steps 3 and 4 to complement non-reproducible Google Scholar results with results that can be reproduced.

- Primary/Citation-based Search - Web of Science
- Supplementary/Expert-based Search - Google Scholar, ProQuest, and Snowball Sampling

- The results of the Google Scholar search were prescreened during the collection process. Articles were added to libraries associated with each focused search. Only new articles were added to subsequent search libraries. Each search yielded fewer and fewer relevant articles because search strings were designed to ensure overlap and total coverage of the subject. This procedure did not allow for the number of results to be reported. When searches were carried out again to obtain these numbers, few articles returned were already in existing libraries. This demonstrated the degree to which our Google Scholar searches were not reproducible and were instead a near random grab of literature. To complement this random grab, updated search strings were run through ProQuest in addition to Google Scholar.

Search String Development

Initial search strings included all initial inclusion terms but were refined to the strings below after a few trials (2.2, 2.3). Below are the justifications for each edit or addition to the search strings applied in the first iteration of searches.

- Removed the redundant use of *culvert* and terms that do not stand without *culvert, shelving and staged barrel.*
- Removed *directive techniques* and *aquatic barriers* because they describe practices.
- After the searches below are screened and assessed we may choose to follow up with a practice focused search involving these terms.
- Refined *transportation structures* and *surface transportation structures* to *transportation* and *surface transportation*
- *Hotspots* and *habitat connectivity* were suggested but were not included because they are too broadly applicable and not necessary for this initial search.

- We may choose to use them in subsequent searches, focused on leveraging BMDPs to do more than just reduce WVCs

- Added "*roadkill mitigation.*"

Below are justifications for each edit or addition to the search strings applied after the preliminary screening was completed, and full-screen decision trees were tested (piloting) (2.3). The second and final iteration of searches reflect the recommendations of science librarians, Stephanie Blair and Diana Hartle, and expert freshwater ecologist, Mary Freeman.

- The first iteration of search strings were updated because of gaps identified in backwards and forwards searches which quickly produced literature that was directly relevant to the review objectives but was not captured in search results.

- *Directive techniques* and *other practices* were not included in the second iteration of search strings because they did not add to the number of returns in either search engine.

- *Transportation* and *surface transportation* were removed to better focus results on hydraulic structures.

- *Hotspots, habitat connectivity* and *hot-spot-road* were not included because of their broad applications.

- Search strings were not broken up by hydraulic structure because of the large character limits and operator capabilities of Web of Science and ProQuest.
  - https://images.webofknowledge.com/images/help/WOS/hs_search_operators.html
  - https://proquest.libguides.com/proquestplatform/tips

- Terms associated with project objective were added to better target practices rather than processes. These terms were added as a separate group using the AND operator to effectively dictate that search results contained relevant hydraulic structures AND interactions AND objectives.

First Iteration of Search Strings - Pilot

Please note that the presence and absence of quotations, parentheses, and all-caps operators all have meaning in a Boolean search.

Culvert Focused Search

- Web of Science (26) - Search in: [Web of Science Core Collection] and [All Editions]
  - [All Fields]: culvert* OR bridge* OR underpass* OR “floodplain relief” OR “stream crossing” OR “perched crossing” OR “drainage structure”
  - [AND] [All Fields]: “road mitigation” OR “roadkill mitigation” OR roadkill* OR “road mortality” OR “road ecology” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions"
  - [AND] [All Fields]: “wildlife crossing*” OR “wildlife passage*”
- Google Scholar (104) *executed 1st*
  - site:gov (“culvert” OR “stream crossing” OR “perched crossing”) AND (“road mitigation” OR “roadkill mitigation” OR “roadkill” OR “road mortality” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions")
  - site:gov (“culvert” OR “stream crossing” OR “perched crossing”) AND (“road ecology”)
  - site:gov (“floodplain relief” OR “drainage structure”) AND (“road mitigation” OR “roadkill mitigation” OR “roadkill” OR “road mortality” OR “road ecology” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions")

Bridge Focused Search

- Web of Science (10) - Search in: [Web of Science Core Collection] and [All Editions]
  - [All Fields]: bridge
  - [AND] [All Fields]: stream OR creek OR river
  - [AND] [All Fields]: “road mitigation” OR “roadkill mitigation” OR “roadkill” OR “road mortality” OR “road ecology” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions"
- Google Scholar (12) *executed 3rd*
  - site:gov (bridge) AND (stream OR creek OR river) AND (“road mitigation” OR “roadkill mitigation” OR “roadkill” OR “road mortality” OR “road ecology” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions")

Underpass Focused Search

- Web of Science (16) - Search in: [Web of Science Core Collection] and [All Editions]
  - [All Fields]: underpass
  - [AND] [All Fields]: stream OR creek OR river
  - [AND] [All Fields]: “road mitigation” OR “roadkill mitigation” OR “roadkill” OR “road mortality” OR “road ecology” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions"
- Google Scholar (5) *executed 4th*

- site:gov (“underpass”) AND (“river” OR “stream” OR “creek”) AND ("roadkill” OR “road mitigation” OR “road ecology” OR “road mortality” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions")

Water Adjacent Transportation Search

- Web of Science (35) - Search in: [Web of Science Core Collection] and [All Editions]
  - [All Fields]: transportation OR “surface transportation”
  - [AND] [All Fields]: stream OR creek OR river OR wetland OR pond OR lake
  - [AND] [All Fields]: “road mitigation” OR “roadkill mitigation” OR “roadkill” OR “road mortality” OR “road ecology” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions"
- Google Scholar (100) *executed 2nd*
  - site:gov (transportation OR “surface transportation”) AND (river OR stream OR creek) AND ("roadkill” OR “road mitigation” OR “road ecology” OR “road mortality” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions")
  - site:gov (transportation OR “surface transportation”) AND (wetland OR pond OR lake) AND ("roadkill” OR “road mitigation” OR “road ecology” OR “road mortality” OR "animal-vehicle collisions" OR "wildlife-vehicle collisions")

Updated Search Strings

Please note that the presence and absence of asterisks, quotations, parentheses, and all-caps operators all have meaning in a Boolean search.

- Web of Science (77) - Search in: [All Databases] and [All Collections]
  - [Abstract]: culvert* OR bridge* OR underpass* OR "floodplain relief" OR "stream crossing*" OR "perched crossing*" OR "drainage structure*"
  - [And] [Topic]: roadkill OR "road ecology" OR "road mortalit*" OR "animal-vehicle collision*" OR "wildlife-vehicle collision*"
  - [And] [Topic]: "wildlife passage " OR “animal passage” OR "wildlife crossing" OR "animal crossing*" OR “road use” OR "road mitigation*"

Filters

- [Publication Years]: 2003 – 2023 (2 excluded)
- [Document Types]: Meetings [Exclude] (4 excluded)

Duplicates removed: 3

Final count: 68

9 duplicates removed once merged with prescreened pilot results. Final Peer Review Total: 92 citations

- Google Scholar (6)
  - site:gov (culvert) AND (roadkill OR "road mortality" OR "animal-vehicle collision" OR "wildlife-vehicle collision") AND ("wildlife passage " OR “animal passage” OR "wildlife crossing" OR "animal crossing" OR "road mitigation")
  - No filters applied; no duplicates observed.
  - 3 citations removed in pre-screening
- ProQuest (75) - Search in *Agriculture & Environmental Science Collection, Dissertations & Theses @ University of Georgia, ProQuest Dissertations & Theses Global,* and the *Biological Science Collection.*

o culvert* OR bridge* OR underpass* OR "floodplain relief" OR "stream crossing*" OR "perched crossing*" OR "drainage structure*" [in] [TITLE]
o [And] roadkill OR "road ecology" OR "road mortalit*" OR "animal-vehicle collision*" OR "wildlife-vehicle collision*" [in] [Anywhere]
o [And] "wildlife passage " OR "animal passage" OR "wildlife crossing" OR "animal crossing*" OR "road use" OR "road mitigation*" [in] [Anywhere]

Filters
o [Publication Years]: 2003 – 2023 (2 excluded)
o Duplicates removed: 6
o Final Count: 67
o 0 duplicates removed once merged with prescreened pilot results and updated Google Scholar Search.
o Final Grey Lit Total: 95 citations
Grey and primary literature results had 17 duplicates reducing the grey lit total to 112 citations and primary lit total to 90.

Review Methods

Search execution and screening will loosely follow the recommendation outlined by Foo et al., 2021 in Figure 3 depicted below.

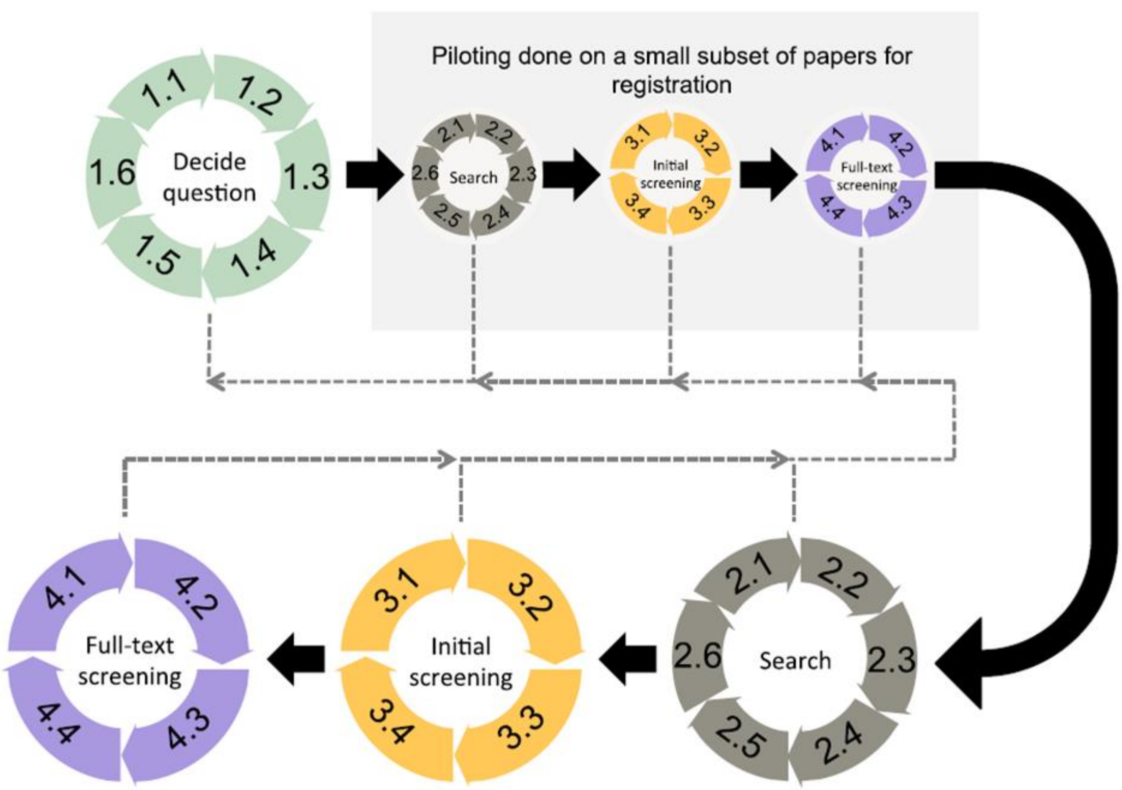

Figure 3. Search and screening workflow based on Foo et al., 2021

Detailed instructions on how to execute searches on Wed of Science, Google Scholar, ProQuest and the Snowball Sampling can be found in the *Search Methods* document. This document includes procedures for duplicate removal and backwards and forwards searches (2.6).

1. Every article returned in a Web of Science or ProQuest search was exported from the engine and directly imported into the appropriate Zotero folder. Google Scholar searches for state or federal grey literature were pre-screened for relevance before being selected for exportation (added to a reviewer's library).

2. A subset of the articles exported were fully screened to assess search efficacy and to develop and refine decision trees (3.2, 3.3) and a synthesis log (Piloting).

3. Initial screening will move articles from the initial export folder into a relevant folder.

a. Before moving forward with the full-text screening, relevant results will be backchecked with literature identified by expert consultants and other project participants.

4. Full-text screening will move articles from a relevant folder to the appropriate practice or process folder. These articles will be used in the final synthesis.

Decision Trees

Initial screening - pilot

- Decision tree (3.1)
1. Published 2003 or after?
  - Yes, go to 2
  - No, leave it where it is
2. About WVC reduction **or** wildlife use of hydraulic structures?
  - Yes, go to 3
  - No, leave it where it is
3. Do they mention bridges, culverts, underpasses **or** relevant mitigation practices **or** species use of these structures?
  - Yes, move to relevant folder
  - No, leave it where it is
- Objectives:
  - identify articles for subsequent backward and forward searches (2.4).

- identify relevant articles (3.4).

Full-text Screening

- Decision tree (3.1)

4. Primary literature: published 2003 or after?
- Yes, go to 5
- No, leave it where it is

5. About wildlife use of hydraulic structures (culvert, bridge, underpass) or contains relevant information about hydraulic structure design specifications that facilitate wildlife movement?
- Yes, move to the appropriate folder and note relevant information in the synthesis log.
- Example: has info about wildlife using a structure that is designed to convey water (process)
- Example: has info about wildlife using a structure that is designed to convey water and/or info on the design specifications of the structure(s) used. (process/practice)
- Example: has info about wildlife using an underpass or bridge that was not designed to convey water but does have information about design specifications and the effect on wildlife use (practice)
- No, leave it where it is

- Objectives:
- Sort relevant articles based on content and data (practices and processes) (3.4).
- **Practices (or mitigation measures)**: articles that contain content or data on practices have information like recommended design specifications for culverts, bridges, underpasses, or other roadway features that either facilitate wildlife's use of under-crossing or reduce wildlife-vehicle collisions.

Practices are the objective of this literature review.
- **Processes (or patterns)**: articles that contain content or data on processes have information like statistics on WVC or undercrossing use. They may contain information about the factors contributing to WVC or under-crossing use, but they do not contain specific design specifications. Information on processes or patterns of WVC or under-crossing use is not the objective of this literature review, but it may help motivate or support our final recommendations.
- **Practices and processes will likely co-occur**. Place articles with both practices and processes in the practices folder.
- Identify articles for backwards and forwards searches

Reviewers will meet weekly to reassess and update review and synthesis methods

Synthesis Methods

Synthesis log incorporated into the full-text screening process.

APPENDIX II. BRIDGE AND CULVERT DESIGNS FOR REDUCED WILDLIFE-VEHICLE CONFLICTS AND IMPROVED CLIMATE RESILIENCY: PHASE II-a

Exhibit A. STATEMENT OF WORK

Research Proposal for the

GEORGIA DEPARTMENT OF TRANSPORTATION

Bridge and culvert designs for reduced wildlife-vehicle conflicts and improved climate resiliency: Phase II-a

The University of Georgia Research Foundation (UGARF)
Mailing Address: 310 East Campus Rd, Tucker Hall 409, Athens, GA 30602-1589Proposal

Date: September 2023

Submitted by
Principal Investigator:
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Proposed contract period: 12 months

Total contract amount: $ 100,000

Funding Agencies:
Georgia Department of Transportation and Federal Highway Administration GDOT supporting office: Environmental Services
Submitted to: Kamari Jordan
Office of Performance-based Management and Research Georgia Department of Transportation 600 West Peachtree Street NW Atlanta, GA 30308 Skamatkar@dot.ga.gov

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INTRODUCTION

Bridge and culvert design primarily involves safely passing floods and debris while minimizing instability and maintenance requirements. However, innovative bridge and culvert designs also have the potential to reduce wildlife-vehicle conflicts (WVCs) by facilitating the safe passage of wildlife beneath roadways. An estimated 1-2 million crashes between motor vehicles and large animals occur annually in the U.S., causing approximately 200 human deaths, 26,000 injuries, and at least $8 billion in property damage and other costs (Pew 2021). Georgia is among the 20 states with the highest risk of WVCs (State Farm 2020). Current bridge and culvert design methods do not include guidance on incorporating elements that simultaneously reduce the likelihood of WVCs while improving hydraulic performance and climate resilience to achieve a higher level of public safety. Further, permitting of structures by environmental agencies is sometimes delayed by wildlife passage concerns. Thus, there is an opportunity to concurrently address these concerns while enhancing public safety and infrastructure resiliency.

PROBLEM STATEMENT AND LITERATURE REVIEW

Current bridge and culvert design methods do not include guidance on incorporating elements that *simultaneously* reduce the likelihood of WVCs and improve hydraulic performance and climate resilience (i.e., flood and debris conveyance with sufficient freeboard) to achieve a higher level of public safety. Further, permitting of structures by environmental agencies is sometimes delayed by wildlife passage concerns. Thus, there is an opportunity to concurrently address these concerns while enhancing public safety and infrastructure resiliency.

Our team has undertaken a Phase I study to identify opportunities to simultaneously improve road safety, reduce WVCs, effectively ensure water and debris conveyance capacity, enhance ecosystem connectivity, and reduce costs and maintenance requirements. In Phase I, we reviewed 741 publications related to reducing WVCs and improving hydraulic structures with emphasis on 171 most important publications for further analysis. We found that several recommendations for enhancing wildlife passage through hydraulic structures for reduced WVCs have garnered sustained support for the past twenty years. These ideas include emulating natural environments, making passages shorter when possible, using the appropriate cross-sectional dimensions, including top openings where feasible, creating dry paths or ledges, using natural materials and cover, and managing fencing and vegetation to increase utilization. Results of the literature review suggest that there is sufficient knowledge to move forward with developing design guidelines for multi-objective hydraulic structures that reduce WVCs, better convey floods, and improve aquatic connectivity. Design modifications for flood and sediment conveyance under climate change are in accordance with several modifications that also reduce WVCs and promote aquatic connectivity.

Most traditional hydraulic design standards of waterway crossing structures like bridges and culverts are mainly based on the hydrodynamic modeling of the design peak flow that the structure conveys. Likewise, culverts in rural areas are often designed based on flow calculated using a design rainfall intensity of at least a 50-year return period (Nuannukul, 2021). However, extreme weather is resulting in higher riverine flows due to rainfall pattern changes and increased storm intensities (Groisman, et al., 2001). Therefore, integrating climate change approaches into design methods is necessary to enhance the resiliency of structures.

According to the Savannah District's Note of the 2021 Nationwide Permit Regional Conditions, the U.S. Army Corps of Engineers recognizes the need for a comprehensive approach to culvert design, especially in light of climate change. Under these regional conditions, culvert replacement or installation requirements on perennial streams generally require culverts to match (or under specific situations exceed) the typical width of the stream channel. Also, they must handle flows above bank full without causing flooding or disrupting the natural hydrology of adjacent areas and be installed at a relatively flat gradient to allow substrate to colonize the culvert’s interior and maintain natural flow velocity (USACE Savannah District Regulatory, 2021). This approach, in concordance with the US. Fish and Wildlife Service, aims to improve aquatic ecosystem connectivity, but also represents an opportunity to simultaneously benefit ecological systems and society by improving wildlife passage and reducing WVCs.

Aside from the urgent necessity of climate adaptation measures, many other factors, such as the increasing demand for mobility of people and goods, and the desire to reduce vehicle maintenance costs, suggest that public transportation networks must be improved. According to the latest infrastructure report (ASCE's 2021 Infrastructure Report Card, 2022), most hydraulic structures in the United States have been graded with C, stating that further maintenance procedures related to replacement or structural improvements are required in the near future. This scenario leads the opportunity to assess the viability of analyzing co-benefits associated with environmental issues such as WVCs.

Linear infrastructure and traffic have an ecological effect on individual wildlife, populations, communities, and landscapes (Van der Ree et al., 2015). One of the most relevant is the barrier to movement due to natural habitat fragmentation. Forming gaps in habitat can modify the movement patterns of wildlife and likely increase wildlife mortality. Therefore, researchers have been trying to identify a solution over the past two decades that considers all aspects, such as habitat fragmentation, barrier movement, WVCs, and economic losses.

Several worldwide studies have documented successful road crossing designs using under-and overpass techniques and identified the benefits of implementing different mitigation measures (Clevenger and Waltho 2000; Glista et al., 2009; Rytwinski et. al, 2016; Marangelo 2019; Brunen et al., 2020; Drasher and Murdoch 2021; Warnock-Jeteau, et al., 2022; Santos et al., 2022). However, these studies lack crucial elements to assess these approaches, such as the cost of implementation, operation, and maintenance. For example, the overpasses structure, which is a terrestrial animal crossing structure that has been broadly implemented in Canada and Europe (Glista et al., 2009). This structure has a high cost associated with its construction and maintenance, while the prevalent use of larger animals is sporadic, resulting in a low cost-benefit ratio. On the other hand, recent studies about underpass structures, specifically culverts, have shown a high potential to be used by various wildlife species at crossroads (Yanes et al., 1995; Rodriguez et al., 1996; Clevenger and Waltho 2000), incorporating feature improvements into designs to allow animal passage (Marangelo 2019) as a mitigation measure.

Implementing mitigation measures for reducing WVCs needs to integrate the analysis of several factors that potentially affect the ability of a crossing structure to facilitate wildlife movements (Glista et al., 2009). Some of those factors can be grouped into two categories: ecological variables (e.g., noise level tolerance, reproductive species cycles, distance to ecological hotspot edges, animal sensitivity to human presence) and structural variables (e.g., slope, openness ratio, length, presence of water, substrate type, dimension) (Warnock-Juteau et al., 2022; Clevenger et al., 2001; Grilo et al., 2022; Glista et al., 2009). Consequently, a systematic approach is lacking to determine the optimum combination of parameters that enhance hydraulic performance while providing a safe wildlife passage to reduce WVCs and provide resilience infrastructure adaptation.

As this project's Phase I findings have shown, hydraulic structures represent a potential opportunity to help as mitigation measurements of WVC, enhancing the terrestrial and aquatic organisms crossing and simultaneously improving safe flood and debris conveyance. This opportunity likely increases if additional practices are included in the design approach (i.e., fencing, adjacent vegetation, natural substrate, openness, width, and length variations), pointing to the necessity to adapt traditional design practices to achieve safe roads, resilient infrastructure and advance toward more comprehensive approaches that enhance both public safety and ecosystem connectivity.

GOALS AND OBJECTIVES

This Phase II research aims to identify locations in Georgia where there are opportunities for simultaneously enhancing culvert hydraulic performance and safe wildlife passage for reduced WVCs, and developing case studies, demonstrations, and training opportunities. The objectives of Phase II are to:

- Building on the results of the Phase I project and knowledge sharing with GDOT drainage design practitioners, identify the best opportunities for innovative culvert and bridge design with the existing design and permitting processes.
- Present a review of the culvert design standards in the context of increasing rainfall intensity for climate resilience.

- Provide guidance on the use of culvert practices and designs that are most likely to both reduce WVC and safely convey floodwaters and debris in a changing operating environment (increased rainfall intensity), as appropriate for different GA regions.
- Propose a spatial prioritization protocol to identify the best locations and opportunities to implement innovative designs that improve organism passage, climate resilience, and ecosystem connectivity while reducing WVCs, based on the definition of variables that influence the simultaneous achievement of objectives. We anticipate our analysis will includes several variables, including vehicle collision hotspots, current hydraulic structure characteristics, flood vulnerability assessments, and aquatic ecosystem barrier inventories, among others.
- Provide preliminary recommendations for the GDOT Hydraulic Design Manual, including guidance on where (and for which taxonomic groups) various features of vegetation management and/or fencing strategies are appropriate and when they are inappropriate due to debris, flow intensity, inundation, and biological considerations.
- Conduct a stakeholder/expert drainage design exchange workshop on practical approaches to combining hydraulic design methods for sediment and debris transport, organism passage, and innovative techniques to reduce the likelihood of WVCs.

SIGNIFICANCE OF RESEARCH

The benefits of this project will include reduced WVCs, reduced permitting times, improved climate resiliency for bridges and culverts, and lower maintenance costs because features that facilitate the safe passage of wildlife can, in many instances, also facilitate the safe passage of floods and debris. Safe passage of wildlife and floods ultimately promotes public safety and reduces costs.

WORK PLAN AND SCHEDULE

The total project duration is 12 months. Phase IIa of the project is divided into **six** tasks to provide specific base information and methodologies to quantify the best practices for integrating hydraulic design with wildlife passage for reduced WVCs.

Task 1: In-depth literature review (second stage Lit-review) to extract context-specific recommendations for minimizing barrier effects, enhancing wildlife crossings, and understanding the complex relationship between hydraulic structures design approaches and WVC reduction, with a special emphasis on culverts and multiuse underpasses.

Task 2: A review and summary of the culvert design standards in the context of climate resilience under increasing rainfall intensity.

Task 3: Learn from current GDOT drainage practices through **knowledge sharing meetings** between GDOT and the research team to identify the best opportunities for innovative culvert design. This task will consist of three virtual or in-person meetings where we will collaboratively identify i) current bridge and culvert design, permitting, and implementation practices in GA, ii) innovative design practices to propose for various GA ecoregions and regulatory contexts, and iii) opportunities to integrate recommendations into the GDOT drainage manual.

Task 4: Expert and Stakeholder Workshop for hydraulic design related to detailed guidance on using practices and culvert designs with the highest likelihood of reducing WVCs and safely passing floods and debris in a changing operating environment (increasing rainfall intensity) appropriate for different regions of GA.

Task 5: Spatial prioritization protocol to spatially identify the best opportunities and locations for implementing innovative designs that improve organism passage, climate resilience, and ecosystem connectivity while reducing WVCs.

Task 6: Phase II-a knowledge transfer that uses the results of the validation of the in-depth literature review and an analysis of workshop results to identify context-specific recommendations for minimizing barrier effects and enhancing wildlife crossings, with a special emphasis on culverts and multiuse underpasses for eco-regions of Georgia. A report appendix resulting from this task will be the first version of recommendations proposed as best practice designs to achieve the multipurpose objectives in the DOT drainage manual.

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Table 4. The actions required for Phase IIa planning, broken down by timeline.

		Month											
Tasks	**Duration**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Task 1: In-depth literature review (second stage Lit-review) to extract context-specific recommendations for minimizing barrier effects, enhancing wildlife crossings, and understanding the complex relationship between hydraulic structures design approaches and WVC reduction, with a special emphasis on culverts and multiuse underpasses.	8 months												
Task 2: A review and summary of the culvert design standards in the context of climate change	8 months												
Task 3: Learn from current GDOT drainage practices through **knowledge sharing meetings** between GDOT and the research team to identify the best opportunities for innovative culvert design. This task will consist of three virtual or in-person meetings where we will collaboratively identify i) current bridge and culvert design practices in GA, ii) innovative design practices to propose for GA ecoregions, and iii) opportunities to integrate recommendations from the GDOT drainage manual.	7 months												

Task 4: Expert and Stakeholder Workshop for hydraulic design related to detailed guidance on using practices and culvert designs with the highest likelihood of reducing WVCs and safely passing floods and debris in a changing operating environment (increasing rainfall intensity) appropriate for different regions of GA.	2 months						■	■					
Task 5: Spatial prioritization protocol to spatially identify the best opportunities for implementing innovative designs that improve organism passage, climate resilience, and ecosystem connectivity while reducing WVCs.	8 months	■	■	■	■	■	■	■	■				
Task 6: Phase II-a Tailor-made knowledge transfer: a proposal (Chapter on the final report) that includes the results of the validation of the in-depth literature review to extract context-specific recommendations for minimizing barrier effects and enhancing wildlife crossings, with a special emphasis on culverts and multiuse underpasses for eco-regions of Georgia, including the analysis of the workshop results as well. This document will be the first version of the recommendation proposal for best practice designs to achieve the multipurpose objectives.	4 months							■	■	■	■		
Final Report Preparation	2 months										■	■	
Final report Review and Revision	1 month												■

Kickoff (KO), Mid-Point (MP), Wrap-up (WU) and Quarterly Project Progress Meetings (PPM)		**KO**			**PPM**		**MP PPM**		**PPM**			**WU**	
Quarterly Report (Q#), Draft Final Report (DFR), and Final Report (FR)					**Q1**				**Q2**			**DFR**	**FR**

SUMMARY OF DELIVERABLES

Phase IIa:

- Quarterly progress reports
- Draft final report (after being reviewed and edited by a professional editor)
- 2-page Project Summary Flyer
- Final report

IMPLEMENTATION

No databases, geodatabases, or physical data will be delivered to GDOT. No software applications, widgets, or automated toolboxes/utilities will be delivered to GDOT. No technology transfer is expected to occur to handoff to GDOT IT for installation, further development, or maintenance/support. If the research team elects to develop IT in the course of the project, GDOT Procedure 13-6 - IT Development Procedures (http://mydocs.dot.ga.gov/info/gdotpubs/publications/13-6) shall apply.

Permitting and design of new road construction and culvert replacement projects offer statewide opportunities to reduce wildlife-vehicle conflicts via designs that provide for safe passage of both floods and wildlife. Guidance developed for Georgia could ultimately inform TRB efforts to reduce WVCs and improve infrastructure resilience.

In addition, the research outcomes would be used by GDOT as a starting point to further hydraulic design standards development. Phase IIa will provide in-depth information regarding methodologies and state-of-the-art advances to GDOT to assess the potential to implement multi-purpose mitigation measurements in their structure maintenance and replacement, and spatial prioritization approach to identify potential sites to simultaneously improve organism passage, climate resilience, and ecosystem connectivity while reducing WVCs.

This stage offers the basic principles for upcoming steps in the project that will assist GDOT in engineering design and enhancing public safety. This will be achieved by offering design suggestions and illustrating the success of the new hydraulic design manual recommendations through case study examples while also exploring their feasibility for implementation.

BUDGET

The total project budget is $100,000. The budget on the following page shows the distribution of project costs. Bledsoe's salary will be charged during summer Maymester; therefore, summer salary and fringe rates apply. Travel funds are requested for academic conference travel for the graduate student to present results of the literature review to transportation practitioners. Funds are requested for a technical editor (Sarah Buckleitner $1500).

SUPPORT REQUIRED FROM GDOT

- Provide existing data related to hydraulic structure characteristics and locations. Provide existing data on wildlife vehicle conflict characteristics, locations, state and dimensions.
- Provide existing data related to road flood event records.
- Provide details on the current methods used for drainage design in the state of Georgia.
- Provide existing H&H data for case study selection and execution.
- Provide existing traffic data.
- Provide existing data on wildlife vehicle conflict characteristics and locations.
- Participate in knowledge sharing workshop on current design and permitting processes to maximize relevance and utility of the research products.

Table 5. The total project budget for Phase II outlined below.

Personnel		**Annual Rate**			% Effort Person Months		**Total**
Principal Investigator					%		
Brian Bledsoe		192,342	Academic Salary			-	-
			Benefits @	36%		-	
		64,114	Summer salary		1%	641	
			Benefits @	22.00%		141	
Co-PI		151,720	Academic Salary		1%	1,517	
Nathan Nibbelink			Benefits @	37%		561	
Co-PI		152,268	Calendar Salary		1%	1,523	
John Maerz			Benefits @	37%		563	
Key Personnel		57,012	Calendar Salary		8%	4,561	
Vanessa Kinney Terrel			Benefits @	40%		1,824	
Key Personnel		63,000	Calendar Salary		27%	16,928	
Alec Nelson			Benefits @	40%		6,771	
Key Personnel		44,000	Calendar		1%	440	

			Salary					
Bryce Martin			Benefits @	48%			211	
Key Personnel (Technical Editor)		77,000	Calendar Salary			2%	1,502	
Sarah Buckleitner			Benefits @	37%			556	
Key Personnel		67,806	Calendar Salary			2%	1,356	
Kevin Samples			Benefits @	40%			542	
Key Personnel		69,620	Calendar Salary			0%	-	
Jennifer Martin			Benefits @	40%			-	
Graduate Assistants PhD	1	69,830				25%	17,460	
			Benefits	5%			873	
Graduate Assistants MS	1	64,458				0%	-	
			Benefits	5%			-	
Undergraduate Students	-	4,096					-	
Total Personnel (includes fringe)							57,971	
Total Fringe							5,272	
TRAVEL							**941**	

Domestic Travel						941	
Domestic Travel - conferences							
SUPPLIES						**3,966**	
Material and supplies - Computing						3,866	
Material and supplies - Office						100	
OTHER DIRECT COSTS						**11,196**	
Graduate Tuition	1	10696				10696	
Publications journal / reporting							
workshop expenses						500	
Total Direct Costs						**74,074**	
***Modified Total Direct Costs**						**63,378**	
Indirect costs @		35.0%	TDC			$ 25,925.81	25,926
Total Costs						**100,000**	**100,000**

Personnel		**Annual Rate**			% Effort Person Months		**Total**

Principal Investigator					%		
Brian Bledsoe		192,342	Academic Salary			-	-
			Benefits @	36%		-	
		64,114	Summer salary		1%	641	
			Benefits @	22.00%		141	
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Graduate Assistants PhD	1	69,830			25%	17,460	
			Benefits	5%		873	
Graduate Assistants MS	1	64,458			0%	-	
			Benefits	5%		-	
Undergraduate Students	-	4,096				-	
Total Personnel (includes fringe)						57,971	
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TRAVEL						**941**	
Domestic Travel						941	
Domestic Travel - conferences							
SUPPLIES						**3,966**	
Material and supplies -							

Computing							3,866	
Material and supplies - Office							100	
OTHER DIRECT COSTS							**11,196**	
Graduate Tuition	1	10696					10696	
Publications journal / reporting								
workshop expenses							500	
Total Direct Costs							**74,074**	
***Modified Total Direct Costs**							**63,378**	
Indirect costs @		35.0%	TDC				$ 25,925.81	25,926
Total Costs							**100,000**	**100,000**

APPENDIX III. LITERATURE REVIEW DATABASE

This appendix refers to the resulting database of the search and screen criteria methodology application to the sources of information reviewed. *The synthesized literature sources included in this file were used to identify the practices and processes related to mitigating WVC and promoting wildlife use of passages respectively. Also, this file includes the identification of hydraulic structures reported in the literature source, and the species group as well.* ***See attached file, Review_Synthesis.xlsm for full database****.*

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