NDOT Research Report

Report No. 701-18-803 TO 2 Part 3

TPF-5(358)
PART 3 - IMPROVING CONNECTIVITY: INNOVATIVE FIBER-REINFORCED POLYMER STRUCTURES FOR WILDLIFE, BICYCLISTS, AND/OR PEDESTRIANS FINAL REPORT

September 2022

Nevada Department of Transportation
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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
701-18-803 TO 2 Part 3		

4. Title and Subtitle	5. Report Date
Improving Connectivity: Innovative Fiber-Reinforced Polymer Structures for Wildlife, Bicyclists, and/or Pedestrians Final report	August 4, 2020 6. Performing Organization Code
7. Author(s) Matthew Bell, Rob Ament, Damon Fick, Marcel Huijser	8. Performing Organization Report No.
9. Performing Organization Name and Address Western Transportation Institute College of Engineering Montana State University Bozeman, MT	10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Nevada Department of Transportation 1263 South Stewart Street Carson City, NV 89712	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Engineers and ecologists continue to explore new methods and adapt existing techniques to improve highway mitigation measures that increase motorist safety and conserve wildlife species. Crossing structures, overpasses and underpasses, combined with fences, are some of the most highly effective mitigation measures employed around the world to reduce wildlife-vehicle collisions (WVCs) with large animals, increase motorist safety, and maintain habitat connectivity across transportation networks for many other types and sizes of wildlife. Published research on structural designs and materials for wildlife crossings is limited and suggests relatively little innovation has occurred. Wildlife crossing structures for large mammals are crucial for many highway mitigation strategies, so there is a need for new, resourceful, and innovative techniques to construct these structures. This report explored the promising application of fiber-reinforced polymers (FRPs) to a wildlife crossing using an overpass. The use of FRP composites has increased due to their high strength and light weight characteristics, long service life, and low maintenance costs. They are highly customizable in shape and geometry and the materials used (e.g., resins and fibers) in their manufacture. This project explored what is known about FRP bridge structures and what commercial materials are available in North America that can be adapted for use in a wildlife crossing using an overpass structure. A 12-mile section of US Highway 97 (US-97) in Siskiyou County, California was selected as the design location. Working with the California Department of Transportation (Caltrans) and California Department of Fish and Wildlife (CDFW), a site was selected for the FRP overpass design where it would help reduce WVCs and provide habitat connectivity. The benefits of a variety of FRP materials have been incorporated into the US-97 crossing design, including in the superstructure, concrete reinforcement, fencing, and light/sound barriers on the overpass. Working with Caltrans helped identify the challenges and limitations of using FRP materials for bridge construction in California. The design was used to evaluate the life cycle costs (LCCs) of using FRP materials for wildlife infrastructure compared to traditional materials (e.g., concrete, steel, and wood). The preliminary design of an FRP wildlife overpass at the US-97 site provides an example of a feasible, efficient, and constructible alternative to the use of conventional steel and concrete materials. The LCC analysis indicated the preliminary design using FRP materials could be more cost effective over a 100-year service life than ones using traditional materials.

17. Key Words	18. Distribution Statement
Wildlife crossing, fiber reinforced polymer structure, fiber reinforced polymer materials, bridge, wildlife vehicle collision, highway safety, mitigation measure	No restrictions. This document is available through the: National Technical Information Service Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	101	

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Improving Connectivity: Innovative Fiber-Reinforced Polymer Structures for Wildlife, Bicyclists, and/or Pedestrians

Final Report

by

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A report prepared for the

Technical Advisory Committee
Pooled Fund Study TPF-5(358) Task 1
Cost Effective Solutions
Nevada Department of Transportation
Carson City, NV

Small Urban, Rural, and Tribal Center on Mobility (SURTCOM)
http://surtcom.org/

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September 13, 2022

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1. BACKGROUND

Ecologists and engineers are constantly exploring new methods and adapting existing techniques to improve mitigation measures that increase motorist safety and wildlife species conservation. It is estimated that over one million wildlife-vehicle collisions (WVCs) with large mammals occur annually in the United States, which result in billions of dollars of property damage, tens of thousands of personal injuries, and hundreds of fatalities (Huijser et al., 2008; Sullivan, 2011). There are currently over 20 various types of WVC mitigation measures (e.g., underpasses and overpasses with fencing, standard and enhanced signs, animal detection-driver warning systems) that can reduce collisions with wildlife, some are highly effective, others are not (Huijser et al., 2021). When wildlife infrastructure is designed and used properly, it can reduce collisions with wildlife up to 99% (Braden et al., 2005; Clevenger et al., 2022; Feremanga, 2017; Huijser et al., 2009; Rytwinski et al., 2016). Crossing structures, combined with fences, are some of the most highly effective mitigation measures that are employed around the world due to their ability to not only reduce WVCs with large animals and increase motorist safety; but, they also provide an additional benefit by maintaining habitat connectivity across transportation networks for many types and sizes of wildlife (Ford et al., 2017; Sawyer & Rodgers, 2015).

The length and width of wildlife overpasses continue to challenge engineers and architects. Recent designs have commonly considered spans over six lanes of traffic and the crossing currently in development for Highway-101 in Liberty Canyon, California will exceed 10 lanes. These crossing widths will require bridge spans that may exceed 60 meters (m) (197 feet [ft]) in length. Common widths of wildlife overpasses have been designed from 30-60 m (98-197 ft) and wider. These design requirements result in large structures. In addition, many are designed to incorporate native habitats, some with forests, that require deep soils that become heavier when saturated by rain and snow melt. The design of overpass structures to support these types of static and environmental loads over multi-lane highways results in high construction costs (e.g., materials, skilled labor, heavy equipment, construction time). An estimate for the Highway-101 overpass in Liberty Canyon is $78 million (Smith, 2022). Not all wildlife crossing structures are in forested environments or are designed for large focal species that require large, wide crossing structures; therefore, many overpasses can be smaller and less expensive than the largest of crossings that capture the public’s attention.

The location of these structures, in conjunction with fencing, depends on a highway’s WVC rates with large animals, wildlife movement needs, local topography, and other site-specific factors. Often, because of their cost relative to other mitigation measures, overpasses and underpasses are used sparingly. Almost 90% of all WVCs in the United States occur on two lane roads (Huijser et al., 2008). In another study, in the largely rural state of Montana, nine out of the top ten WVC hotspots during the fall migrations of wildlife occur on two-lane highways (Creech & Callahan, 2016). Thus, shorter spans and more economical structures will be needed more frequently than the larger structures.

Overpass structures are generally designed using pre-cast or cast-in-place concrete and steel materials. The landscape surface on overpasses is often designed after the completion of the overpass structure, although there is evidence that projects may be more successful if the integration of landscape components are considered during the preliminary or initial design stage. The use of concrete and steel materials have limitations that include long construction durations that result in traffic control, delays, and detours for up to six months or more. The large size and limited mobility of equipment required during erection of the superstructure also contribute to construction inefficiencies and higher costs.

In addition to the restrictions with construction and design, concrete and steel are vulnerable to environmental freeze-thaw cycles that results in cracking, salt intrusion, and reinforcement corrosion. Regular under deck inspections are required to identify potential fatigue cracks or corrosion. For steel members made from non-weathering steels, routine painting is required for their maintenance.

At the end of their service life, these permanent structures often require significant rehabilitation and/or increased maintenance, making bridge replacement a more economical option for bridge owners. Recent research found that steel bridges are at risk of increased structural failure rates during normal loading if average temperatures continue to rise over the next 100 years (Palu & Mahmoud, 2019). The steel bridges in the Northwest U.S. where there are more pronounced differences between the temperatures during bridge construction, and the predicted future temperatures, are more likely to see this effect. Moreover, approximately five percent of global CO_2 emissions originate from the manufacturing of cement, and it is the third largest source of carbon emission in the United States (Huntzinger & Eatmon, 2009).

Published research on bridge designs and materials for wildlife crossings is limited and suggests relatively little innovation has occurred for these specialty structures (Lister et al., 2015). Given wildlife crossing structures are a critical contribution to highway mitigation strategies for reducing WVCs while also providing habitat connectivity, the need for new, resourceful, and innovative techniques is warranted.

2. PROJECT OVERVIEW

This project explored the promising application of fiber-reinforced polymers (FRPs) to wildlife overpass structures and related crossing design elements. It investigated the material properties of FRP, the applications to bridge structures, and the promising features for other wildlife crossing infrastructure components. The report highlights the versatility of FRP materials and their beneficial outcomes when compared with traditional bridge construction using concrete and steel materials. It evaluated whether FRP structures are capable of meeting bridge design specifications and can potentially result in lower life cycle costs. FRP materials have the potential to provide new materials for wildlife crossings that are more efficient in construction, require less maintenance, and ultimately are more adaptable than traditional materials (Bell et al., 2020). The project evaluated what FRP materials are being made in North America and which of these are potentially suited for wildlife overpass structures and which may be useful for other wildlife crossing design elements.

Through a competition for a design site, seven applications from state transportation agencies sought to have the FRP wildlife overpass designed for their specific highway location, one with high animal-vehicle collision rates, and one to help overcome the barrier or partial barrier effect to wildlife movement caused by the road and its traffic. This project developed a design of an FRP wildlife overpass for the selected application for a specific site in northern California and explored opportunities for the inclusion of FRP materials in the overpass structure including design elements in wildlife crossings (e.g., fence posts). Working with California Department of Transportation (Caltrans) and professionals from other local and federal agencies, the project benefited from their expertise to help address challenges and identify solutions to incorporate FRP materials into a wildlife crossing design. Furthermore, this project explored potential uses of FRP materials for wildlife infrastructure beyond existing transportation applications.

The use of an existing highway location provided an opportunity to demonstrate a real-world setting for the application of FRP materials in a wildlife crossing design. In addition, a team of ecologists, engineers, planners, wildlife biologists, and landscape architects was convened to worked together to explore, identify, and evaluate a variety of applications of existing commercially available FRP materials; ones that can be used at the project site or elsewhere across the North American road network. Although there are countless uses of the FRP materials discussed in this report, this project selected and focused on those applications relevant to the design of a wildlife overpass structure and its related elements at the selected California highway mitigation site.

This report describes how the infrastructure design for the specific site in this project could be adapted to other wildlife crossings sites with different design requirements (i.e., 3-lane and 4-lane highways, narrower or wider crossing structures, habitat types).

Another section of the report examines whether FRP materials used for wildlife overpasses could be adapted for bicycle-pedestrian (bike-ped) crossings. This section will cover different design requirements used in current bike-ped crossings and how they could be adapted to incorporate FRP materials.

The final section of the report describes the life cycle cost analyses of FRP materials. They include materials, fabrication, and transportation estimates from FRP manufacturers. The cost-benefits section also conducted a cost comparison of different bridge structures with the FRP structure designed for this project. To obtain this comparison, the dimensions of the FRP infrastructure designed for the California site were compared to the information gathered regarding other wildlife overpass structures using steel and concrete in other parts of North America.

3. LITERATURE REVIEW

3.1. Fiber-Reinforced Polymers

Fiber-reinforced polymers are a composite material of structural fibers set in a mold of thermoset resin (Figure 1). Thermoset resins do not get soft at elevated temperatures because they contain cross-linked polymers. Thus, once the polymers have cured, they cannot be remolded into a different shape. Therefore, thermoset resins restrain the fibers against buckling to allow the transfer of shear stress between them (Kemp & Blowes, 2011; Nijssen, 2015). Virgin polyesters, vinyl esters and epoxies are the most commonly used thermosetting resins for FRP materials, but synthetic, bio-based, and recycled polymers are also used to adhere fibers together (Gkaidatzis, 2014; Kim, 2017). The type of resin and fibers selected depends on the purpose of the structure. The different chemical properties result in different performance characteristics. Some of these materials are more resistant to environmental elements and can increase the life expectancy of a structure.

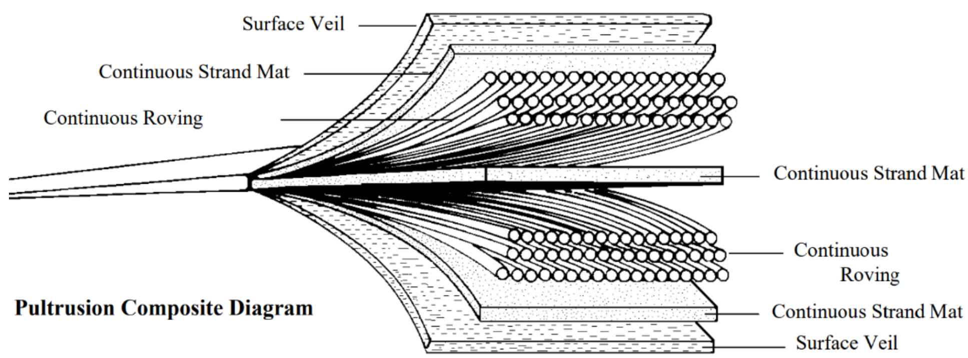

Figure 1: General configuration of structural fibers distributed throughout thermoset resin (Creative Pultrusions Inc., 2019).

Fiber-reinforced polymers can outperform concrete and steel because of their dimensional stability, high strength, and light weight. Case studies show the average FRP bridge is half the weight of a steel bridge with the same strength; and it is five-times lighter than its concrete equivalent (Davalos et al., 2013; Smits, 2016; Sonnenschein et al., 2016). Additional benefits of a lighter structure are reduced energy and construction costs (e.g., manufacturing, emissions, labor, transportation, supporting structures, construction time). Depending on the properties of the resins and fibers used within FRP structures, they can be fire and UV resistant, electromagnetically transparent, impact resistant, have low thermal conductivity, provide no electrical conductivity, and have low maintenance costs (Demkowicz, 2011; Gaggino, 2012; Katangur et al., 2006; Kemp & Blowes, 2011; McConnell, 2011; Nijssen, 2015; Sonnenschein et al., 2016).

3.1.1. Sustainability

Sustainability is the process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and transition of institutional decisions are in harmony to meet human needs and aspirations (Brundtland, 1987). The production of FRP composites is currently in a grey area regarding sustainability. They are mainly derived from non-sustainable products which include crude oil, natural gas, chlorine, nitrogen, and glass. Looking at this factor may make it seem like FRP materials cannot be sustainable, but sustainability is measured by a number of factors (e.g., minimum resource use, low environmental impact, low human health risk) (Zaman et al., 2014).

The manufacturing of virgin FRP materials produces less greenhouse gases and energy consumption than manufacturing of steel, aluminum, and concrete (Strongwell, 2009). When FRP composites are compared to other traditional materials like wood and terra cotta, the total life-cycle assessment of FRP contributes to its viability as a green building product, and now qualifies for many credits under the Leadership in Energy and Environmental Design (LEED) building rating (Beetle Plastics, 2013). The initial price of FRP materials and manufacturing is generally higher than other traditional methods, but when life-cycle analyses include external costs (e.g., environmental, sustainability, social) and service life, FRP construction is favored by up to 14% (Ilg et al., 2016). As FRP technologies advance and become more accepted the initial cost is likely to decrease. Furthermore, incorporating more bio-based resins and recycled materials will favor the use of FRPs over traditional methods. Using FRP materials in place of steel and concrete for bridge construction significantly reduce the carbon and energy footprint during the construction stage, and even further during the 100-year service life of FRP structures (Richardson, 2019).

There are two main techniques to recycle FRP materials after their service life – they can be ground up and used as a filler or broken down to repurpose the resin and fibers (Oliveux et al., 2015). The best method of recycling is to reclaim the fibers and use them in other composites, and the left-over resin powder can be used in cement kilns to replace coal (Job, 2013). Carbon fibers are better at retaining their strength and thermal properties than glass after they are repurposed from FRP materials (Bank & Yazdanbakhsh, 2014).

3.1.2. Resins

The type of resin used to manufacture FRP materials directly relates to the beneficial properties of these structures to resist various physical (e.g., wheel rolling, collisions, debris) and environmental (e.g., moisture, oxidation, ultra-violet [UV] rays) impacts (Nijssen, 2015). Although every material has some form of degradation, these effects can be significantly reduced by changing the chemical composition of the polymers. The addition of stabilizers can improve the performance to some degree. Other types of fillers can increase electrical and thermal conductivity (e.g., aluminum powders, carbon fibers, and graphite), improve bonding of polymers to fibers (e.g., silanes and titanites), act as flame retardants (e.g., chlorine, bromine, phosphorous, and metallic salts), reduce costs (e.g., calcium carbonate, silica, and clay), and change resin colors (e.g., metal oxides, chromates, and carbon blacks). Generally, the smaller the particles added, the greater the boost in stiffness, but the original resin begins to lose impact strength as the level of fillers increases (Power, 2018). The FRP resistance to environmental factors, therefore, can only be risen to a certain degree before the mechanical properties of the material are affected.

Material testing on glass and carbon FRP shows that after 1000 hours of exposure to environmental conditions (e.g., fresh and saltwater, dry heat, alkali, freeze-thaw, UV, and gasoline fuel) there was less than a 10% change in the elastic properties, and the change in tensile strength was less than 15% when comparing mean values (Demkowicz, 2011). Absorbing stabilizing agents can improve the resistance to degradation. Zinc and titanium dioxide nanoparticles, for example, allow only 5% of the degradation that occurred on the unprotected FRP after a week of UV exposure (Katangur et al., 2006). Furthermore, these tests commonly expose FRP materials to levels of UV exposure not found on earth, i.e. short wavelengths less than 290 nanometer (nm). Longer wavelengths of 365 nm, equal to the UV rays that make it through the ozone, were found to be incapable of inducing a chemical change in high molecular weight polymer structures (Shanti et al., 2017).

Another characteristic of FRP structures that can be improved through resin fillers is their water resistance, which is relevant in many types of moisture exposed applications (e.g., marine lock-gates and pilings, decking, sewage pipe and wastewater ductwork, water filtration and storage, oil pipelines). Their moisture resistance is determined by the manufacturing process and the chemical composition of the FRP. These properties allow the resins to reduce the amount of water absorbed and limit swelling of the FRP. Some resins can absorb water through osmosis at a microscopic level, but the process is reversed when the FRP is dried (Nijssen, 2015). If resins swell with water and then dry, this can increase the degradation rate of the polymer (Gaggino, 2012). However, applications of moisture resistant resins can be applied to the outside of the FRP structure if the use of these resins become cost prohibitive for use throughout the entire mold.

Manufacturing FRP composites is most commonly done using virgin resins, but the use of bio-based polymers and recycled plastics are becoming more common as researchers and engineers try to develop more sustainable solutions with eco-friendly products. Bio-based polymers are synthetic materials that are processed from vegetable products (e.g., starch, proteins, and oils). These products are commonly derived from soy beans, potatoes, corn, and flax, but can also be derived from a large number of other grains and seeds (Wool, 2005). Bio-based resins still have a long-life span but do degrade faster than virgin polymer-based resins. This is even more pronounced when the resins are recycled. The use of recycled polymers has been associated with a downgrade of mechanical properties (Gkaidatzis, 2014). This creates challenges for using them in FRP structures because they are more difficult to include complex fiber distribution throughout the mold. Therefore, recycled plastics are commonly used in non-structural applications.

3.1.3. Fibers

Most of the strength of an FRP structure comes from the choice of fibers used within the composite mold. Glass is the most commonly used fiber. Carbon and aramid fibers have improved material properties although generally cost more than glass. Fibers are randomly assorted within the mold as short strands of fibers or layered as fiber mats to create a resin matrix. This application of fibers can be compared to rebar in reinforced concrete, at a much smaller scale, dispersed throughout the entire composite material. At the microscopic level, the mechanical properties of these composites are determined by the orientation and distribution of the fibers, and can increase the strength of FRP materials if the fibers are oriented in the direction of the highest stresses (Roylance, 2008). As seen in Table 1, there are stark differences between the material properties of FRP depending on the type of fibers used.

Table 1: Stress-strain relationship of the various kinds of FRP composites in comparison with steel reinforcement (from Sonnenschein et al., 2016).

Properties	Carbon fibres		Glass fibres		Aramid fibres		Basalt fibres	Steel
	HS (High Strength)	HM (High Modulus)	E-glass	S-glass	Kevlar 29	Kevlar 49		
Density ρ [kg/m^3]	1800	1900	2540	2530	1440	1440	2700	7850
Modulus of elasticity E [GPa]	230	370	72	89	83	124	90	200
Tensile strength [MPa]	2480	1790	3400	4600	2920	3600	4000	500
Extension [%]	11.00	0.50	2.12	1.93	3.50	2.90	2.25	2.50

The use of natural fibers is gaining popularity because of the energy input required to produce inorganic synthetic fibers (e.g., glass, carbon). Bio-based fibers can be derived from plants (e.g., seeds, stems, fruit, leaves, grass) and animals (e.g., fur, wool, silk). Some of the strongest plant based fibers include flax, hemp, and jute (Gkaidatzis, 2014). However, their mechanical strengths are less than inorganic synthetic fibers as shown in Table 2. One of the main drawbacks of natural fibers are also less structurally durable. They are more flammable and water absorbent and degrade faster from UV radiation.

Table 2: Mechanical properties of flax, hemp, jute, e-glass, and basalt fibers (from Gkaidatzis, 2014).

Properties Fibre	Modulus (GPa)	Strength (MPa)	Density (g/cm3)	Specific Modulus	Specific Strength
Basalt	90	1430-4900	2.67	33	~ 1185
E-glass	72	2000-3500	2.54	28	~ 1080
Flax	50-70	500-900	1.4-1.5	~ 41	~ 480
Hemp	30-60	300-800	1.48	~ 30	~ 370
Jute	20-55	200-500	1.3-1.5	~ 27	~ 250

The fiber-volume ratio is determined by the percentage of fibers within the total volume of the composite. Using the same type of fibers, higher fiber volume ratio typically result in better mechanical properties of FRP composites (Endruweit et al., 2013). Depending on the composite material design requirements, the optimal fiber volume ratio is between 30-70%. The ratio can be as high as 90% if all the fibers are in the unidirectional orientation, but a decrease in strength can occur because there is not enough space for the resins to fully surround and bond with the fibers (Fu et al., 2019).

The type and configuration of fibers is also based on the desired strength requirements. The material properties of FRP composites can be determined by two methods: experimental strength analysis or theoretical micromechanics. Experimental strength analysis uses structural testing to identify limits of stress and strain under tension, compression, and shear loading. The theoretical method evaluates the individual strengths of fibers and resins at the microscopic level then adds their strengths together. The strength properties of the FRP using the theoretical method are calculated using known fiber and resin material properties and volume ratios.

3.2. FRP Manufacturing Process

Many advancements made in the design and manufacturing process of FRP materials over the last three decades have resulted in currently two main techniques used to create FRP products for bridge infrastructure: pultrusion molding and vacuum assisted resin transfer molding. Each manufacturing process creates different types of structural members that allows engineers to create custom shapes and molds to fit project needs.

3.2.1. Pultrusion Molding

The first method to create structural FRP composites is through the process of pultrusion; where the fibers and resin are pulled through a mold simultaneously to create continuous members (Figure 2). They can be formed into bars, plates, structural tubing, and other cross-sectional shapes. These FRP elements are commonly referred to as 'lumber' because of their similarity to girders made from wood and steel with a uniform shape that can be cut to any length. Forming the structural members is an intensive process but is extremely efficient when large quantities of a standard section are needed. The production of standard sized units makes this method ideal for the creation of repetitive building techniques, i.e., fence posts and wall barriers. Commonly made of recycled polymers, these methods have been adopted as a solution for replacing old and deteriorating structures (Groenier et al., 2011).

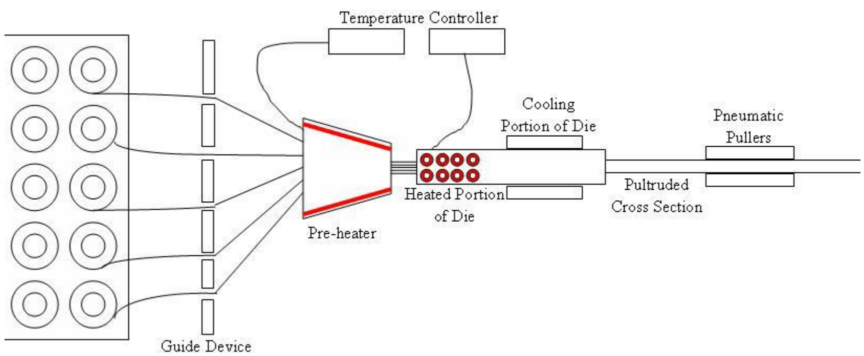

Figure 2: Schema of how pultrusion members are formed (Kamble, 2008).

3.2.2. Vacuum Assisted Resin Transfer Molding

The second fabrication method to create FRP structures is the use of vacuum assisted resin transfer molding; a process that pumps resin through custom shaped molds with the desired fiber layouts (Figure 3). This manufacturing technique is used to create custom molded shapes and can integrate other materials for different applications of civil infrastructure. Core inserts can be applied in geometric formations (e.g., squares and hexagons) to reduce weight by creating void spaces that reduce the amount of resin and fibers required. For these cases, the fibers are arranged around the core material to produce strong, lightweight, and durable FRP structures. The molds can result in free-formed standalone (Uni-mold) FRP bridges or designed as large decks and casings that are constructed with steel and/or concrete materials to create hybrid FRP structures.

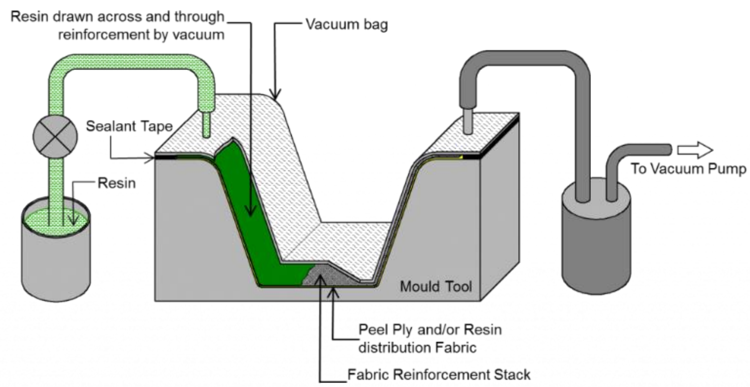

Figure 3: Schema for how vacuum assisted resin transfer molded structures are formed (CSIR, 2018).

3.3. FRP for Bridge Infrastructure

The application of FRP composites in transportation began during World War II, they were used for airplane parts. More recently, these materials are now commonly used in multiple types of road and bridge infrastructure that include, asphalt; structural pilings and decking in marine settings; water drainage systems; FRP wraps for repair and strengthening of concrete, metal and wood structures; FRP reinforcement in concrete; traffic barriers/fenders; and multiple types of pedestrian and traffic bridge applications (Frankhauser & O'Connor, 2015; Smits, 2016; Sonnenschein et al., 2016).

The creation of FRP pultruded lumber in the 1990's allowed engineers to create different applications for this adaptable and long-lasting composite. One of the first reported FRP pedestrian bridges was created in 1995 in Harlingen, the Netherlands (Smits, 2016), while the first vehicular bridge made of FRP composites was built in 1998 in Fort Leonard Wood, Missouri. The U.S. Army continued to make advancements and built the first vehicular bridge made of recycled plastics in 2009 in Fort Bragg, North Carolina, that is capable of carrying a 70-ton military tank (Chandra & Kim, 2012). The construction costs of FRP bridges are competitive with other materials, however the life-cycle costs are significantly less for FRP materials (Richardson, 2019). Furthermore, the offsite fabrication and light weight characteristics contribute to more efficient on-site construction.

For bridge structures, the two manufacturing methods allow several bridge configurations to be constructed with FRP. The opportunities to combine materials created from these processes for bridge infrastructure is limitless. To simplify the different types of bridges, they have been divided into three types: pultrusion, hybrid, and uni-mold bridges.

3.3.1. Pultrusion Bridges

Pultrusion-style pedestrian bridges are assembled using steel and lumber construction methods with different geometric FRP cross sections (e.g., square, rectangle, i-beam, etc.) and are commonly connected with stainless-steel bolts. The stainless-steel hardware increases the service life of the connections to the long-life expected from FRP materials. An example of a pultrusion style pedestrian bridge using FRP I-beams can be seen in Figure 4. The beams are connected with galvanized-steel bolts. This bridge spans 29 m (95 ft) and is 1.8 m (6 ft) wide. The pedestrian bridge in Marshall, California was designed with a live load of 293 kilograms per square meter (kg/m^2) (60 pounds per square foot [psf]).

Figure 4: Pultrusion-style pedestrian bridge in Marshall, CA. (Creative Pultrusions Inc., 2019).

Pultrusion-style bridges can be installed quickly. They can be constructed near the construction site and then erected on to their abutments to avoid costly delays and detours. The glass FRP (GFRP) bridge in Spain (Figure 5) is an example of this process. The bridge spans 38 m (125 ft) and is 3 m (10 ft) wide. It was assembled and erected using accelerated bridge construction methods that only closed vehicle and railway traffic for three hours while the bridge was slid into place.

Figure 5: Glass FRP arched pedestrian bridge, Lleida, Spain (Fiberline Composites, 2019).

3.3.2. Hybrid Bridges

Hybrid structures consist of the integration of FRP composites with other structural materials such as concrete and steel. They are currently the most widely used FRP bridge system. Hybrid bridges combine the benefits of FRP with the familiarity and experience that exists with more traditional materials. The most common hybrid structure includes installing an FRP deck on concrete or steel girders. These girders are erected using traditional methods with an FRP deck that replaces traditional pre-cast concrete, cast in place concrete, or steel deck materials. The 22 m (72 ft) hybrid vehicle bridge over B3 highway in Germany utilizes an FRP deck on top of steel girders (Figure 6). Connecting the deck beforehand allowed the entire structure to be erected at one time, reducing the time required to open the bridge after installation.

Figure 6: A hybrid traffic bridge over B3 highway in Germany (Fiberline Composites, 2006).

Another version of a hybrid bridge focuses on the superstructure to create spans using a combination of FRP, concrete, and steel. The hybrid composite beam (HCB) system conceals steel and concrete materials within an FRP exoskeleton. This system takes advantage of the strength of concrete and steel, and the durability of FRP under environmental exposure. The steel and concrete are concealed by the FRP structure, less material is required to equal the strength of a similar girder, or beam, made without FRP. The concrete and steel are also protected from corrosion and will not require maintenance over their service life. The HCB unique configurations optimize its performance and leads to lightweight, cost-effective, and durable structural supports (Seoud, 2013).

A third type of an FRP hybrid bridge that has become more popular among bridge engineers is the concrete-filled FRP tube (CFFT) system because of their quick installation time, high strength, and long lifecycle. The CFFT system is created by inflating plastic bags inside of fiber-woven sleeves, bending it to the desired arch, and vacuum infusing resin through the tube. These light-weight empty FRP tube arches are positioned on-site without the use of heavy-lifting equipment into cast-in-place concrete foundations and connected together with FRP corrugated panels. A 38 centimeter (cm) (15 inch [in]) diameter FRP tube without concrete that spans 14.6 m (48 ft) and has a rise of 3.4 m (11 ft) only weighs 113 kilograms (250 pounds [lbs]) (Advanced Infrastructure Technologies, 2019). Before the last panel is connected at the top of the arch, the arched tubes are filled with concrete. Concrete can also be poured over the FRP panels for additional lateral force resistance. The tubes and the panels are the only structural components required. A schema of the CFFT bridge system can be seen in Figure 7.

The FRP arch described above has three functions: they act as a stay-in-place form for the concrete, are an exoskeleton reinforcement for the concrete so no rebar is needed inside the tubes, and as a protective layer for the concrete. These arches have been tested in the lab using accelerated fatigue testing and show they retained their full capacity after testing was completed, demonstrating the residual strength of the arches was equivalent to their initial strength (Dagher et al., 2012). Testing has shown that the CFFT arches are extremely ductile compared to conventional reinforced concrete (Walton, 2015; Walton et al., 2016). In addition, sand-coating the inside of the FRP tube reduces slipping between the concrete and the FRP tube, increasing the flexural strength and stiffness of the CFFT members (Ali & Masmoudi, 2018). Examples of different types of bridge spans using the CFFT system can be seen in Figure 8.

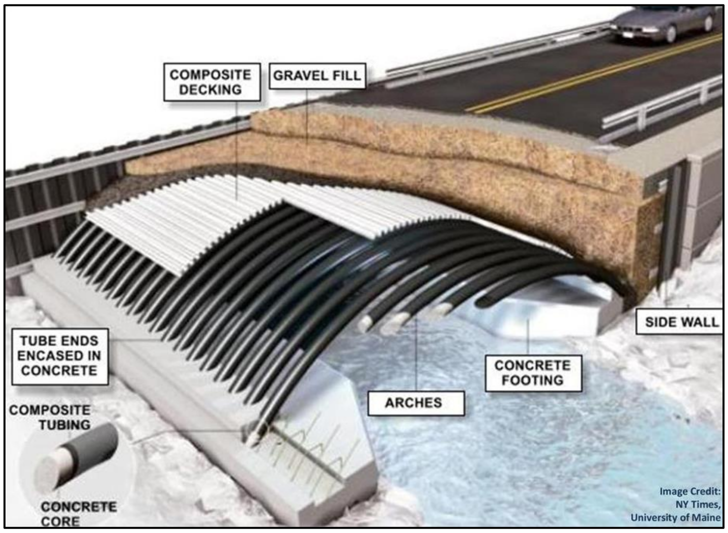

Figure 7: Schema of the CFFT bridge design developed by Advanced Infrastructure Technologies (Advanced Infrastructure Technologies, 2019).

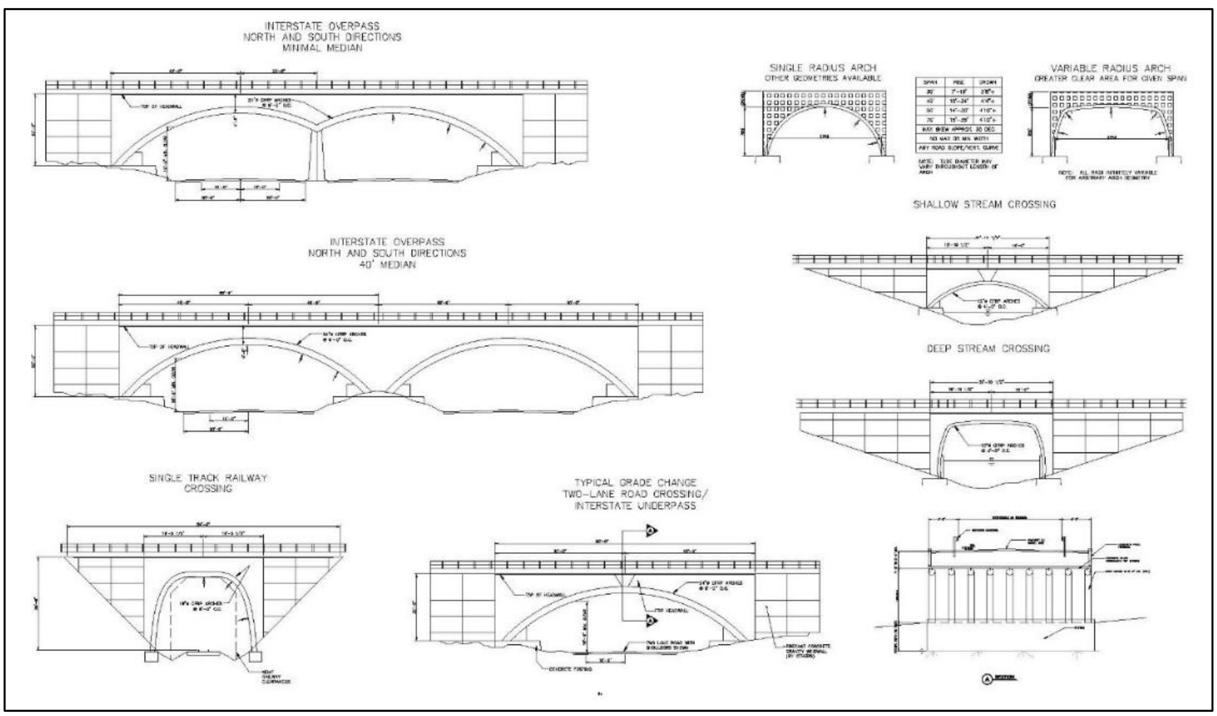

Figure 8: Different geometry applications of CFFT bridge spans (Abatiell, 2018).

Many current applications of CFFT bridges exist as underpasses and support the static and dynamic loads of traffic flow. The McGee Bridge replacement project in Anson, Maine spans 8.5 m (28 ft) and is 7.6 m (25 ft) wide. It was completed, start to finish, in 12 working days and included the removal of the old bridge. Commercial champions of this technique claim a CFFT bridge span can be completed in as little as three days (Milberg, 2018).

These cast-in-place CFFT arches are adaptable to all road types. Consisting of single or double radius arch designs, bridges can be built to span all lanes of traffic or use the median to connect two smaller arches. Although larger FRP tubes that span over 60m are being designed and tested off-site, tubes for shorter span bridges may be constructed on location, reducing the costs of transportation logistics. CFFT bridge designs reduce both life-cycle costs and the carbon footprint of bridge construction due to the manufacturing and construction processes, and reduced maintenance. These structures are already tested to meet the AASHTO requirements for traffic loads and have established design standards (AASHTO, 2013).

3.3.3. Uni-mold Bridges

Uni-mold bridges are FRP structures created with a single vacuum assisted molding process to make one large bridge (Figure 9). They may incorporate other non-structural materials within the mold, but they do not rely on the strength of the material fillers like the hybrid bridges do with concrete and steel. Uni-mold bridges reduce the amount of non-FRP hardware and connections required to build and install the bridge.

Figure 9: FRP ecoduct near Eindhoven, The Netherlands spans 36 m (118 ft) and is 3.5 m (11.5 ft) wide (FiberCore Europe, 2019b).

These bridges allow for the completed structure to be manufactured in the factory, then shipped to the construction site and installed quickly. The wildlife crossing structure near Eindhoven was shipped and installed using one truck and crane (Figure 10, A). There is endless possibility to create unique structures using this method. The uni-mold bridge system can be one of the fastest methods to install an FRP bridge because the abutments can be built ahead of time, potentially with minimal disruption to vehicle traffic, and then the FRP uni-mold bridge is placed on the foundation in one lift (Figure 10, B).

Figure 10: A) FRP uni-mold bridge is delivered in one piece from the factory to the construction site; B) bridge is installed using one crane (FiberCore Europe, 2019b).

3.4. Summary

FRP materials support modular construction, target particular properties, and different methods of fabrication (Davalos et al., 2013; FiberCore Europe, 2007; Groenier et al., 2011; Kim, 2017). The dimensional constraints of FRP products are limited by transportation logistics, not in the structural properties and technology itself. In principle, there is no limit to the dimensions of the FPR elements in a bridge design. The maximum capabilities of this innovative material have not been fully realized and requires additional research (Smits, 2016). To date, published research findings indicate that the expectations for performance and durability are often exceeded. The overall sustainability of FRP structures is not only a function of the material's origin, but also depends on how the materials are used and their specific application. The use of recycled and bio-based materials would improve the environmental benefits of FRP structures; however, the reduction in the service life of these materials offsets the overall sustainability gain when compared to more conventional and durable virgin polymer materials (Gkaidatzis, 2014).

4. FRP MANUFACTURERS AND THEIR PRODUCTS

There are many US and international companies that make FRP products that can be incorporated into wildlife crossing infrastructure. This chapter identifies 21 companies with experience and the capability to manufacturer materials and/or structures suitable for FRP bridge structures.

4.1. FRP Manufacturers for Bridge Elements

Potential FRP manufacturers were initially identified for a design charrette, or a co-laboratory, where engineers, landscape architects, and ecologist first evaluated opportunities for FRP materials to be used for wildlife crossing overpasses. Further research performed during the literature review in Task 1 identified potential manufacturers capable of developing FRP infrastructure elements that are suitable for wildlife crossings.

There are manufacturers from around the world, many based in Europe, that focus on using FRP materials to replace old and deteriorating steel, wood, and concrete bridges. Many of these companies do not produce FRP bridge beams but do provide pultrusion elements that can be used for other elements of wildlife crossing structures. A summary of the manufacturers can be found in Table 3. The table is divided into companies that develop pultrusion-style and vacuum assisted resin transfer moldings. Additional information and technical data provided by these manufacturers can be found in the Appendix A: FRP Manufacturer Information. Most of the technical data was obtained through personal communication as many of the companies do not provide this information on their websites.

Various international and US-based companies listed in Table 3 were contacted by email or phone to determine their ability to provide their products in North America. Many of the international manufacturers were limited by transportation logistics and were not able to deliver FRP structures larger than a standard shipping container to the U.S. Based on the information gathered and exchanged with the 21 companies, the list was refined to a smaller number that were able to meet the requirements of an FRP crossing in North America.

Disclaimer – The information given here is for educational purposes. The companies included in this report met a range of criteria *specific to needs, timeline and location of this project*, based on available information. The information provided in this report should not be considered an endorsement or recommendation of any kind, whether negative or positive, of any product or manufacturer. This report does not contain a comprehensive list of all companies who manufacture FRP structural members for bridges and crossing structures in North America.

Table 3: Summary of the selected FRP manufacturers that are capable of supplying bridge spans or associated elements for wildlife crossing structures.

FRP Companies Capable of Making Wildlife Crossing Infrastructure			
Company	**Country**	**Types of FRP structures**	**Technical Data Available**
Pultrusion Companies			
Composicon	USA	Pedestrian/trail bridges, barrier walls, platforms and walkways, structural fabrications, custom moldings.	NA
Bedford Reinforced Plastics	USA	Trail bridges, grated walkways, and custom shapes	NA
Creative Pultrusions	USA	Trail bridges, decking, wall panels, and structural beams	Material properties, installation guide, design
Axion Structural Innovations	USA	Recycled plastic: boardwalks, decking, support beams, pilings, and foundation mats	Material properties
FiberGrate	USA	Structural profiles, plates, grates, ladders, stairs, platforms, custom molds, and sound barriers (STC of 30 and class 1 fire retardant)	Installation guide, soundscape, some material properties
American Plastic Lumber Inc.	USA	Recycled plastic lumber	Material properties
Liberty Pultrusions	USA	Structural profiles, threads/studs/nuts, rods, precision mechined parts, custom fabrications	Material properties
Tangent	USA	Recycled plastic structural lumber, mats	Material properties
Bedford Technology	USA	Recycled plastic structural lumber, fence posts	Material properties
Strongwell	USA	Bridge decks and superstructures, retaining walls, structural shapes, sound barriers, foam-core building panels	Material properties
Kenway Composites	USA	Pultruded structural profiles	NA
Fiberline	Denmark	Structural profiles, decking, pedestrian bridges, re-bar, and hybrid structures	Some material properties
Vacuum Assisted Resin Transfer Companies			
Advanced Infrastructure Technologies	USA	Bridge in a Backpack (CFFT), composite tub girders	Maintenance, design, installation
Hillman Composite Beams	USA	Hybrid Composite Beams	Material properties of the FRP shell
Guardian Bridge Rapid Construction	Canada	Decks, uni-mold bridges, and hybrid structures	NA
Orenco Composites	USA	Uni-mold bridges with InfraCore technology	NA
Mostostal Warszawa	Poland	Decks, hybrid composite beams and girders	NA
FiberCore Europe	Netherlands	Uni-mold bridges, decks	Technical data sheet
Lifespan Structures	United Kingdom	Uni-mold bridges, decks	NA
Delft Infra Composites BV	Netherlands	Uni-mold bridges	NA
Applied Advanced Technologies	Russia	Uni-mold bridges, pultrusion pedestrian bridges, decks	NA

4.2. FRP Pedestrian and Bicycle Bridges

The use of FRP for pedestrian bridges is well documented. These structures range from pultrusion style bridges constructed using traditional steel and lumber techniques, to entire load-bearing uni-mold FRP structures installed with a single crane lift (Smits, 2016). One of the earlier applications was the replacement of old and deteriorating short-span bridges with FRP. The technology has improved over the years and spans for FRP pedestrian bridges have increased to over 100 ft. This section reviews different pedestrian bridges for each manufacturing method. These applications are readily available and can be implemented as infrastructure projects in North America and around the world.

4.2.1. Pultrusion Bridges

Creative Pultrusions, Inc. is in Alum Bank, Pennsylvania. It is one of the leading manufacturers of pultrusion-style FRP pedestrian bridges. They have created additional companies to form the Creative Composite Group with a focus on engineered solutions that are light-weight, corrosion resistant, and long-lasting. This group consists of Creative Pultrusions, E.T. Techtonics, Composite Advantage, Kenway Composites, and Tower Tech Sustainable Efficiency. Each company specializes in a specific product, but together, these companies manufacture pedestrian bridges, board walks, unique molds, marine and highway infrastructure products, bridge decks, cantilever sidewalks, and fender protection systems, from FRP materials. Working with the Creative Composites Group allows customers to benefit from advanced manufacturing capabilities from their partner companies to create an optimal solution.

Creative Pultrusions provides material properties for their pultrusion elements. This enables the WTI Team to efficiently model different bridge configurations using their cross-sectional shapes. They have been manufacturing FRP products for over 30 years and have created standard designs that are adaptable to many access situations. An example of an FRP pultrusion pedestrian bridge can be seen in Figure 11.

Figure 11: FRP Pultrusion pedestrian bridge built by Creative Pultrusions (Griffith, 2018).

Creative Pultrusions can currently build pedestrian bridges up to 35 m (115 ft) by 5 m (16 ft) wide and have designed and tested a 46 m (150 ft) bridge. The bolted connections of the members can support live load designs of up to 391-439 kilograms (kg)/m^2 (80-90 pounds per square foot (psf)), is significantly less than the estimated load required for this wildlife crossing design, which was estimated around 1,465 kg/m^2 (300 psf). Because of their bridge experience and continued research into increased load designs up to 976 kg/m^2 (200 psf), Creative Pultrusions may be an option for future crossings that support larger loads. While not specifically designed for wildlife, their bridges have been designed for mule trains.

Creative Pultrusions is not the only manufacturer that makes pultrusion style bridges, but most pultrusion style bridges are built in very similar manner. This type of bridge is very adaptable and great for remote locations where lightweight materials will benefit the transportation of the bridge to the construction site. Composicon, Bedford Reinforced Plastics, Strongwell, and Kenway Composites are all U.S. based FRP manufacturers that provide pre-designed and custom applications of pultrusion bridges.

4.2.2. Hybrid Bridges

The creation of hybrid pedestrian bridges is common around the world. Using FRP decks on top of steel or concrete supports provides a long-lasting solution to other traditional materials that have a shorter service life. This section covers a few companies that have built different styles of hybrid bridges from around the world and is intended to show the range of designs possible.

Advanced Infrastructure Technology (AIT) is one of the leading manufacturers of CFFT and are based out of Brewer, Maine. The CFFT is a great solution for short span pedestrian bridges. They are a low-cost solution that can be rapidly built. One example of this FRP technology being used for pedestrian bridges is the Tom Frost Memorial Bridge in Hermon, Maine (Figure 12). The FRP bridge was selected to replace the old wooden bridge after it was damaged by a car that slid off the road. This bridge is designed for a snowmobile groomer and snow loads. The snowmobile bridge is constructed with three carbon-FRP (CFRP) 30 cm (12 in) diameter tubes. The bridge has a 13.7 m (45 ft) span and is about 3 m (10 ft) wide. There is a 20 cm (8 in) concrete deck poured on top of the corrugated FRP panels. This type of hybrid bridge is ideal for arched structures.

Figure 12: A hybrid CFFT pedestrian snowmobile bridge, Hermon, Maine (Advanced Infrastructure Technologies, 2010).

Another common application of hybrid bridges is the use of FRP decking to decrease installation time and extend the service life. Composite Advantage, a subset of the Creative Composites

Group, created thin FRP decking for the top of a 390 m (1,280 ft) walking path near Lake Tahoe, California (Figure 13). There were 32 bridge spans were installed using a lightweight crane. Each deck section was approximately 12 m (40 ft) long and 13 cm (5 in) thick. The decking was designed for a 439 kg/m^2 (90 psf) live load and are coated with a non-slip polymer aggregate surface. The FRP decking weighs 59 kg/m^2 (12 psf) and connected to the steel support spans with stainless-steel bolts.

Figure 13: Hybrid walkway with FRP decking and steel supports near Lake Tahoe, California (Creative Composites Group, 2019).

Applying an FRP deck to steel support spans allows for very large pedestrian bridges to be built. FiberCore Europe created the deck for a 140 m (459 ft) pedestrian bridge over the A27 highway in Utrecht, the Netherlands (Figure 14). This viaduct used a steel support frame for the span with FRP decking. The lightweight decks allowed them to be connected to the steel frame prior to installation, and then the entire structure was maneuvered into place.

Figure 14: Hybrid bridge with FRP decking in Utrecht, the Netherlands (FiberCore Europe, 2012).

4.2.3. Uni-mold Bridges

The uni-mold bridge type is the most customizable system that can create endless unique bridge designs. The span of FRP uni-mold bridges is limited by costs, manufacturing space, and transportation logistics. FiberCore Europe is one of leading manufacturers in the world for uni-mold pedestrian bridges and is based in the Netherlands. Their patented InfraCore™ technology creates very strong and light weight structures. An example of their designs can be seen in the 27 m (89 ft) pedestrian bridge along the hiking path at Lake Czorsztyn, Poland (Figure 15). They have created bridges that are 37 m (121 ft) and plan to build larger bridges in the future. In 2020, FiberCore has made an agreement to allow Orenco Systems, a composites manufacturer in Sutherlin, Oregon, the ability to use their InfraCore™ technology to build uni-mold pedestrian bridges in the U.S.

Figure 15: Example of uni-mold pedestrian bridge built around Lake Czorsztyn, Poland (FiberCore Europe, 2019a)

Lightweight Structures BV is another leading company that makes uni-mold bridges. They created a 54 m (177 ft) arched pedestrian bridge in Nijmegen, the Netherlands (Figure 15). This bridge is used to connect two nature areas near the city. The bridge crosses a water canal and has enough clearance to allow boats to pass underneath.

Figure 16: Arched uni-mold bridge in Nijmegen, the Netherlands (Structurae, 2014).

5. APPLICATIONS OF FRP FOR WILDLIFE CROSSING STRUCTURES

The preliminary technical data collected in Chapter 4 was used to select the most qualified companies, and/or products for the structural design and related elements. The companies were selected based on the following criteria: (1) product capabilities and experience, (2) costs in manufacturing, transportation, and construction, (3) aesthetics, (4) local support and the interest of the manufacturer.

To obtain more detailed information from the selected manufacturers' bridge systems, estimated design loads required for an efficient overpass structure were shared with each company that expressed interest. One of the objectives of this project was to establish criteria for a lighter weight wildlife crossing that is typical of previous wildlife overpass designs in forested environments in North America. For the purpose of identifying potential FRP manufacturers for wildlife crossing structures, the project sought to find the minimum design load required to support the proper function of the crossing. Instead of the typical one meter for soil depth to support a forest, the project reviewed innovative methods of cover and protection for wildlife that would not be reliant on deep soils and a continuous forest cover on top of the structure. The FRP overpass structure used a soil depth of 38 cm (15 in), or 732 kg/m^2 (150 psf) to estimate the design load. In addition to soil, vegetation, sound and light barriers, animal weight, and construction and maintenance loading resulted in a minimum design load of 1,465 kg/m^2 (300 psf).

There are many different types of wildlife overpasses that have been constructed around the world, but no large mammal crossings have used a FRP structure. It is assumed that traditional materials, such as concrete, will be used as part of the California site's design (e.g., foundation, abutments), as a 100% FRP design was not the objective of this investigation. A brief description of suitable companies that manufacturer pultrusion, hybrid, and/or uni-mold bridges for deployment in North America is provided below, followed by examples of underpass structures, and supporting design elements such as jump outs, fencing, and barriers.

5.1. Pultrusion Bridges

To pursue a pultrusion style wildlife overpass, one that supports a minimum load of 300 psf, and is 50 m-wide, would require a structural size that has not yet been produced in North America. The spans that have currently been created in North America via the pultrusion method do not meet the standards required for a large wildlife crossing over an active road needed at the California site. Further research is required to make pultrusion style bridges a suitable solution for large wildlife overpass structures at this time.

5.2. Hybrid Bridges

Hybrid bridges combine the benefits of FRP materials with traditional materials such as concrete, steel, or wood. There are a larger number of companies that are capable of building FRP hybrid bridges than the those producing members by pultrusion methods alone. Companies selected and described below use FRP materials for the main structural supports. Companies that design and fabricate FRP deck panels placed on traditional steel or concrete girders were not considered.

5.2.1. Guardian Bridge Rapid Construction

This manufacturer of FRP products is based in St. Mary, Ontario, Canada. They build wood-based structures that are wrapped in FRP material. The wrapping provides additional strength, as well as protects the wood from environmental degradation. Guardian Bridge has been manufacturing FRP infrastructure products for almost 30 years and designing bridges to the Canadian Highway Bridge Design Code (CHBDC) CAN/CSA 06 and AASHTO specifications. Their products include bridge decks supported by girders, unsupported bridge spans, double and triple tee panels, abutments, wing-walls, and approach slabs. The triple tee FRP bridge, seen in Figure 17, spans 15 m (49 ft) and is made with a wood core and an FRP exoskeleton. The abutments the bridge is placed on is also made out of wood and FRP.

Figure 17: Wood and FRP bridge made by Guardian Bridge Rapid Construction for a two-lane road; A) a triple-tee span being placed by a crane; B) all three spans placed on top of an FRP abutment.

Guardian Bridge Rapid Construction entered a contest hosted by ARC Solutions to develop a wildlife crossing using their innovative materials and design. Their design was a lightweight and versatile structure shown in Figure 18. The bridge incorporated modular construction with smaller bridge segments utilizing a tree canopy on the main span to create multiple routes across the bridge. The bright red bridge was intended to be an iconic structure for humans, signifying the crossing, the landscape and its non-human inhabitants, but is unnoticeable to wildlife that cannot see the color red.

Figure 18: Guardian Bridge Rapid Construction's design of a wildlife overpass for a design competition over Interstate Highway 70 in Colorado (ARC Solutions, 2010).

5.2.2. Hillman Composite Beams

Hillman Composite Beams (HillCB) is based out of Chicago, Illinois. Using decades of experience in bridge design they have developed a structural girder that is an FRP exoskeloton surrounding concrete and steel elements that support the compression and tension loads of a bridge (Figure 19). Their HCB combines durable FRP materials with the low-cost and functional advantages of concrete and steel that result in a cost competative, resilient bridge system that benefits from an extended service life. The internal concrete arch is a parabolic curve that is the proper funicular shape to eliminate flexure in the bridge span. In high seismic regions, the reduced superstructure mass results in substructure costs being reduced by as much as 30%. With years of proven field performance, their HCB is a revolutionay structural technology that demonstrates HillCB's commitment to provide a sustainable solution to deteriorating infrastructure for future generations.

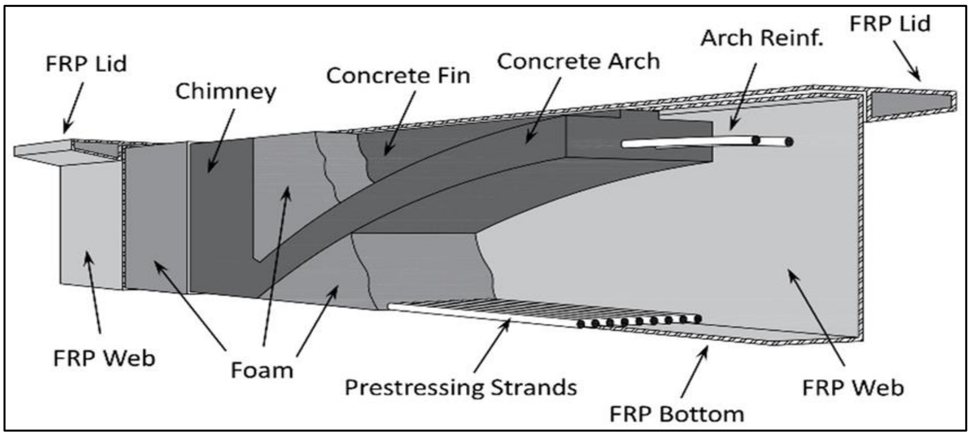

Figure 19: Schema of Hillman Composite Beams' HCB design (Hillman, 2003).

One example of an HCB is the use of a steel-reinforced concrete arch cast inside an FRP girder (Hillman Composite Beams, 2019) and is shown in Figure 19. To maximize the contribution of the FRP to the overall beam strength, foam inserts are used inside the FRP tube to reduce the volume of concrete, resulting in a lighter beam. The internal concrete arch within the HCB FRP girder can be as thin as a couple inches, depending on the design requirements. After the beams are set on a foundation system, they are commonly surfaced with a wearing concrete surface or additional FRP decking.

Hillman's HCB was shown to be stronger than its concrete and steel equivalent and 90% and 66% lighter, respectively (Hillman, 2003). The beam uses about one-fifth the amount of concrete compared to a solid concrete beam with the same strength properties. The reduction in weight increases transportation efficiency and the exoskeleton created by the FRP material results in less maintenance and longer service life when compared to steel and concrete beams. With respect to design requirements, the Hillman HCB system met the provisions of the American Association of State Highway and Transportation Officials (AASHTO) specifications for beam-type bridges (Harris et al., 2016).

To date, HillCB has fabricated over 267 beams, all of which met or exceeded project specifications. Currently the largest bridge span built is 32 m (106 ft) shown in Figure 20, but spans of 37 m (120 ft) or greater are possible. Generally these beams are designed to be flat to accommodate the roadway profile, but there is an upward curvature (camber) to reduce the perceptible bridge deflection due to the permanent loads on the structure. HillCB can increase this camber to provide additional slope used for water drainage, but this can also be done with elevation differences in the supporting bridge abutments. Only 1.5-2% slope in any direction is required to facilitate the water drainage and a minimized drainage slopes would reduce water runoff, thus benefitting vegetation.

These HillCB beams are installed the same way as traditional concrete beams and are typically connected using concrete slab decking. The company is currently looking at using FRP decking to put on top of the HCB that would be able to support earth fill on top. HillCB has not performed a seismic analysis or testing on their HCBs but have validated their panels for blast loads created by vapor cloud explosions in petrochemical facilities. By virtue of their strength combined with low Young's Modulus, when compared to concrete and steel, HCB's remain elastic during large displacement events. HillCB would expect the same behavior for their beams when subjected to lateral seismic loading. They have also done extensive testing on fatigue, serviceability, and strength of their beams, which includes testing on thermal cycling, accelerated UV exposure, salt spray, and lateral impact.

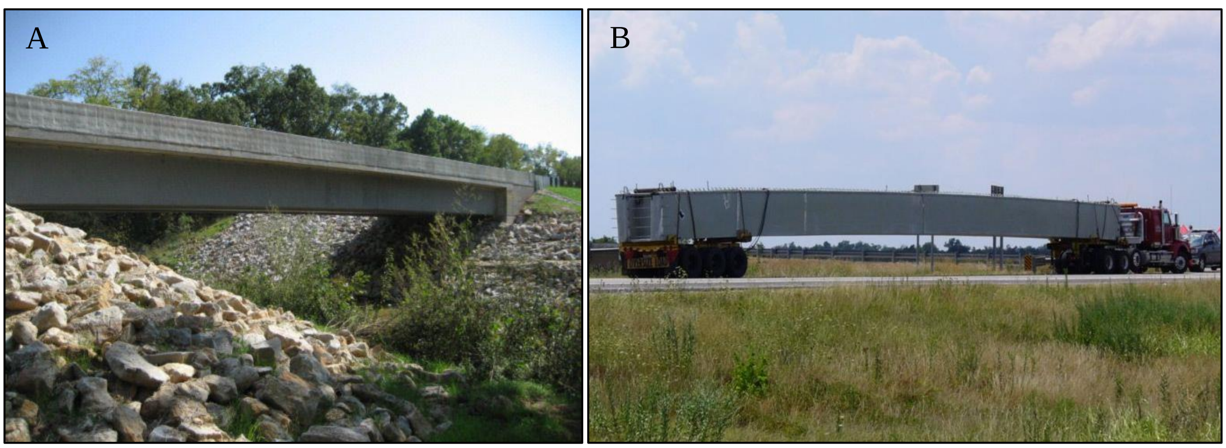

Figure 20: Hillman Composite Beam's HCB bridge near Lockwood, Missouri. A) completed bridge; B) an HCBs being transported on a truck.

HillCBs' engineers typically provide a preliminnary design and share the design tools to allow for the owner to experiment with their desired configuration. A licensed Caltrans structural engineer would be required to certify the engineering calculations and plans for a selected configuration. HillCB prefers to have other engineers engaged in the design process. The turn-around time to fabricate beams is about two months when the factory is in full production. This time depends on the approval of shop drawings and the number of beams ordered.

The special provisions HillCB provided this project are consistent with their design process. These provisions do not include the internal material properties of the concrete and steel inside the HCB. Their design process starts by satisfying live load deflection criterion with a span/depth ratio between Length (L) divided by 18 and L/25, depending on design requirements and magnitude of live loads. The ultimate bending capacity is then checked and is analogous to a reinforced concrete beam. Designing for shear is more complicated because there is load sharing between the concrete rib and FRP laminate webs that varies along the length of the beam.

5.2.3. Advanced Infrastructure Technologies

Advanced Infrastructure Technologies is based in Brewer, Maine, and works closely with the University of Maine's Advanced Structures and Composites Center where they do extensive testing and design. Advanced Infrastructure Technologies (AIT) is an engineering and manufacturing company that supplies advanced composite materials for bridges, while providing low cost solutions to the aging and deteriorating transportation infrastructure industry. They have received numerouse awards and recognition for their innovative and transformative products and systems. By utilizing advanced composite materials to create non-corrosive products, AIT is an industry pioneer and leader in transforming the bridge industry. They have developed two different methods for creating FRP bridge spans that can be used for wildlife crossing infrastructure.

The CFFT bridge system developed by AIT is designed as an arched culvert structure that can be used as an overpass. One example of a bridge that allows traffic to travel over and under the CFFT bridge is shown Figure 21. The largest CFFT span built to date is 21 m (70 ft), but AIT is currently testing spans over 30 m (100 ft). Some of the bridges they have built have had over 4.5 m (15 ft) of rise to them and are able to span a two-lane road.

Figure 21: CFFT bridge built by AIT in Augusta, Maine.

For bridge heights that exceed 5 m (16 ft), the arch tubes are spliced at the apex in the field to avoid overwidth transportation restrictions. However, the splice they have developed does not impact the strength and durability of the CFFTs bridge. AIT uses the Federal Highway Association (FHWA) Technical Manual for Design and Construction of Road Tunnels – Civil Elements to design their CFFT bridge system because the structure was originally designed as a culvert-style bridge to replace deteriorating infrastructure. The foundation system required for the arched structure must be designed for both vertical and horizontal components because of the arch action used to resist the vertical loads. A driven H-pile system, which has been identified by Caltrans engineers as an economical foundation system for the area, may not be capable of resisting the lateral loads.

AIT offers a Mobile Composite Manufacturing Unit (MCMU) to provide an alternative fabrication process than long-distance transportation from Brewer Maine. This equipment was developed as a cost-effective manufacturing process that requires minimal plant/equipment to produce the primary structural FRP tubes of the CFFT bridge. The MCMU is a self-containing 6 m (20 ft) standard shipping container that contains all the necessary tools and equipment that are powered by local energy grids. The unit includes a vacuum pump, air compressor, plugs, and a generator, for the vacuum infusion process. The manufacturing process requires a separate supporting company that is capable of creating the plywood arch forms using a computer numerical control (CNC) machine. The MCMU allows for local and scalable manufacturing at a low capital cost. These manufacturing units can either be purchased or leased; it is normally not cost efficient to ship the MCMU to a local site and train local labor, but projects with large numbers of girders fabricated on site with the MCMU can offset the cost of transportation of finished members. The only restriction would be large, flat, staging area near the construction-site, where the manufacturing takes place.

The second type of bridge developed by AIT, their newest composite bridge system, uses FRP composite tub (CT) girders. Construction of the first bridge using this system was completed in 2021. The CT girder is a long-life solution to traditional steel and concrete, medium span deck bridges at a similar cost. The system consists of a lightweight FRP tub girder (Figure 22) that is simply supported on a typical foundation system with a precast panel or cast-in-place concrete deck. The girders use small foam inserts along the vertical sections to increase the width of the structure while reducing weight. The girder is covered with a non-degradable cap (e.g., FRP, polyvinyl chloride [PVC], or high-density polyethylene [HDPE]) that depends on the loading. If the final beam supports a full 23 cm (9 in) cast-in-place slab, the CT girder would likely be made from 1 cm (0.5 in) FRP sheet stock. If it is supporting a 4in partial-depth precast deck, more economical material thicknesses can be used.

Both FRP and concrete deck materials can be used with the AIT's CT girder. The advantage of concrete decking is that it is a readily accessible material, relatively low cost and provides excellent compressive strengths that optimizes the composite action and reduces overall project costs. However, composite decking like the Atlas corrugated panels produced by AIT can be utilized on shorter length composite girders or for smaller loads. An advantage to the AIT tub girder for wildlife crossings is the potential to leave some of the CT girder uncovered (cut-out) so it can be filled with soil and used for root propagation. A means of transferring the compressive forces and distributing the soil forces to the girders around these cut-outs would be a design consideration for a partially uncovered CT girder.

Figure 22: A section of a CT Girder made by AIT. Foam inserts can be seen in the vertical walls of the girder to help reduce the weight (Francis, 2019).

AIT has done extensive durability testing on their composite structures using accepted criteria for accelerated testing for environmental exposure. The test results exceed these criteria and provide evidence that AIT's FRP products will last 100 years, and possibly longer. The cost of FRP bridge alternatives from AIT have been competitive when compared to other traditional construction methods. One example is the Edmunds Bridge in Maine where costs and impact were compared to a precast concrete alternative by Conspan. The CFFT bridge has a smaller footprint than the precast concrete and therefore has less impact on the surrounding area. It is about 50% the cost of the precast concrete and eliminates the need for staged construction, and traffic management/detours, and it reduces environmental impacts.

5.3. Uni-mold Bridges

Uni-mold FRP bridges are common across Europe with many qualified manufacturers. These companies, however are limited in the geometry of their bridge designs because of size restrictions for shipping, often leading to higher costs. Because of the over-sea transportation challenges of large structures, one European manufacturer of uni-mold bridges, who has located to North America, Orenco Composites, may produce structures large enough to be used for wildlife overpasses and was selected for further evaluation.

5.3.1. Orenco Composites

Orenco Composites is a FRP manufacturer headquartered north of Roseburg, Oregon. Their location is conveniently located approximately 200 miles from the selected project crossing in northern California on U.S. Highway 97 (US-97). Orenco Composites is a division of Orenco Systems, Inc. and has been manufacturing high-strength, water-resistant fiberglass products for more than 30 years. The company's engineers are nationally recognized experts in the fields of fiberglass product development and manufacturing. Orenco builds FRP wastewater tanks, shelters, basins, enclousures for telecommunications, and products used by utility, railroad, aviation, and food industries.

Recently Orenco Composites signed a contract with the FiberCore Europe in January 2020 to use their InfraCore® Inside technology. The InfraCore™ system is a proven cost-effective, easily scalable, strong, lightweight, durable, damage-tolerant, maintenance free, load bearing and fail-safe FRP structure. They achieve these characteristics by using foam blocks within the molds to combine the beneficial properties of sandwich structures and multi-beam plates. InfraCore is a laminate technology which enables the beneficial properties of classic sandwich structures (e.g., light weight, high stiffness, high strength), without the drawbacks (e.g., skin-core debonding, delamination). It has successfully solved one of the major challenges with FRP sandwhich structures by controlling delaminations, especially due to fatigue after impact. FiberCore has demonstrated during the past couple of years cost-effective solutions for the infastructure sector. This has resulted in a wide portfolio of applications, including bridges, bridge decks and marine lock gates. More than 1,000 heavy duty structures with InfraCore Inside technology have been successfully delivered. The inherent fail-safety of InfraCore® has been proven and validated by tests performed by certified institutes and recognized by testing societies.

Orenco Composites has started fabricating pedestrian bridges using InfraCore® technology, The company completed their first bridge mold during the summer of 2020, but construction of the project was delayed due to the COVID-19 pandemic. Orenco expressed interest in expanding their market and working on a wildlife crossing design. With Orenco's InfraCore® technology, designs for North America are no longer limited to the size of a standard shipping container. This allows engineers the freedom to design FRP uni-mold bridges that can span over 30 m (98 ft).

5.4. Wildlife Underpass

A wildlife underpass is a bridge-type structure that supports traffic loads from vehicles above, while providing safe wildlife passage below. Pultrusion-style bridges were built using 100% recycled plastic for trains in 2015 by the manufacturer Axion Structural Inovations shown in Figure 23. Axion recycled structural composite (RSC) was developed in conjunction with scientists at Rutgers University, where it was patented. It is the first known structural product of its kind capable of supporting heavy loads. This is a method that could potentially be used to develop a pultrusion-style wildlife underpass from recycled plastic, but the necessary spans currently limit the potential of this alternative.

Figure 23: Pultrusion-style train bridge built from recycled plastic (Chino, 2011).

A uni-mold wildlife underpass manufactured by Orenco Composites is another option that may be possible, but is limited by the lack completed applications and design standards in the US. FiberCore has limited experience with bridge spans capable of supporting traffic loads and other design requirements that exist along US-97. However, research evaluating FRP uni-mold culvert structures with finite-element analysis has yielded promissing results (Yang & Kalabuchova, 2014) and may be a method that is more acceptable in the future.

5.5. Jump-outs, Fences, and Barriers

Jump-outs (egress ramps that allow animals to escape from the traffic side of a fence), fences, sound and light barriers are some of the design elements that help create a more effective wildlife crossing. That is, they prevent wildlife from entering the roadway which decreases collisions, and direct animals to the crossing structure with helps maintian wildlife movement and landscape connectivity. Sound or light barriers help reduce traffic noise, artifical light from vehicles and other traffic induced deterrents for wildlife to approach and cross the highway using an overpass structure. Fences or other types of barriers along both edges of a structure also keep animals from jumping off overpasses. They are also essential design elements for bicycle and pedestrian bridges.

The design elements that improve the success of wildlife crossings do not require the size, strength and stiffness for bridge girders. There are many companies that are capable of making the FRP pultrusion products (lumber) required to build these design elements. The company below was selected for its proximity to the US-97 site, the availablity of appropriate materials for the design elements, and their interest in wildlife crossing applications for their products. American Plastic Lumber is a single example, among many others in North America that can provide similar, competively priced FRP materials.

5.5.1. American Plastic Lumber, Inc.

American Plastic Lumber, Inc., is based in Shingle Springs, California and is approximately 250 miles from the project's US-97 crossing site. They have been manufacturing maintenance-free recycled plastic lumber products distributed throughout the world for nearly two decades. They offer a large selection of colors, sizes, and grades, for applications such as boardwalks, docks, wharfs, decks, railings, and retainng walls. American Plastic Lumber is capable of providing FRP products that would contribute to a successful wildlife crossing on US-97.

5.6. FRP Materials Available for the Project's Design Tasks

After a broad review of FRP manufacturers across North America, the project was able to identify six FRP companies, in addition to those highlighted above, with commercially available materials that could be adapted for the structural component of the wildlife overpass for the project's site on US-97 in Siskiyou County, California (Table 4). Also identified were numerous North American FRP pultrusion lumber manufacturers with products that could be used for wildlife crossing design elements (e.g., fence posts, decking, sound barriers). From a substantial list of these FRP lumber producers in North America, only one was reviewed and included in Table 4, American Plastic Lumber, because of its proximity to the Caltrans wildlife crossing site.

Table 4: Selected FRP manufacturers best fit for designing and building wildlife crossing infrastructure.

FRP Companies Capable of Making Wildlife Crossing Infrastructure			
Company	**Country**	**Types of FRP structures**	**Technical Data Available**
Creative Pultrusions	USA	Trail bridges, decking, wall panels, and structural beams	Material properties, installation guide, design
Axion Structural Innovations	USA	Recycled plastic: boardwalks, decking, support beams, pilings, and foundation mats	Material properties
American Plastic Lumber Inc.	USA	Recycled plastic lumber	Material properties
Advanced Infrastructure Technologies	USA	Bridge in a Backpack (CFFT), composite tub girders	Maintenance, design, installation
Hillman Composite Beams	USA	Hybrid Composite Beams	Material properties of the FRP shell
Guardian Bridge Rapid Construction	Canada	Decks, uni-mold bridges, and hybrid structures	NA
Orenco Composites	USA	Uni-mold bridges with InfraCore technology	NA

6. US-97 MITIGATION DESIGN LOCATION

6.1. Site Selection

A competitive process was developed, in cooperation with the Pooled Fund Study TPF-5(358) Technical Advisory Committee (TAC) to select a highway site for the Project's FRP wildlife overpass design. A request for proposals was developed and distributed to each of the agencies that contributed to the pooled fund study, along with a set of the selection rating criteria. The 12 TAC members were asked to reach out to personnel in their state or provincial transportation agency, or the Parks Canada Agency, to identify highway segments that would benefit from a future wildlife overpass.

The goal was to have local staff of the agency champion the selected site and help the researchers acquire the necessary site-specific information for the design. Collaboration with agency bridge engineers and planners, willing to share their agency's bridge design requirements, specifications, and construction practices, was determined necessary to achieve a viable FRP wildlife overpass design for the project.

The preferred attributes for the location for an FRP wildlife overpass design included the following:

- The site be a priority that the agency is already planning to address.
- Committed sponsoring agency to invest in WVC mitigation at the site.
- Two-lane road to keep the demonstration FRP project to a reasonable scale.
- Few topographical, hydrologic, or edaphic design challenges.
- High-profile site that with traveling public exposure.
- Prioritized for wildlife rather than livestock.

Six proposed design locations were submitted for the project's TAC to select from; one was located in Nevada and five in California. A brief overview in Table 5 summarizes road segment attributes for each of the proposed locations in relation to the site selection criteria. For more details about the proposed design locations, see Appendix B: Proposed Design Locations.

Table 5: Summary of the six proposed mitigation sites submitted by the TAC.

Road	County, State	Mitigation Plans	# of Lanes	Mitigation Length	Traffic Exposure	Roadway Topography	Target Species
SR-439	Storey, NV	Identified	4	TBD	High	Below grade	Horse
SR-139	Modoc, CA	Yes	2	16 km (10 mi)	Low	Flat	Mule deer
US-97	Siskiyou, CA	Identified	2	16-32 km (10-20 mi)	3600-9000 AADT	Hills and flat	Elk, deer, pronghorn
SR-20	Colusa, CA	Proposed	2	6.4 km (4 mi)	Peak 870 vehicles/hour	Hills and flat	Elk
US-101	Humboldt, CA	Priority	2	4.8-8 km (3-5 mi)	4000 AADT	Flat	Elk, deer, bear
SR-126	Ventura, CA	Identified	4	41.8 km (26 mi)	26000 AADT	Hills and flat	Deer, cougar, bear

NOTE: TBD = To be determined; AADT = Average annual daily traffic

Table 6 was created to rank each location based on the goals of the project. These are subjective rankings based on the information provided in the proposals about the highway segments proposed for mitigation and from agency reports related to the highway and its surrounding area of interest. The WTI Team gave their recommendation, then a vote by the TAC to select the site was held. The highway segment receiving the most votes was selected as the location for the site-specific FRP overpass design.

Table 6: Design site location rankings used to assist in the decision-making process.

Road	County, State	Local Conservation Value	Regional Conservation Value	Highway Mortality	Highway Barrier	Land Use Security	Mitigation Options	Average Value
SR-439	Storey, NV	4	2	5	2	2	1	2.7
SR-139	Modoc, CA	4	3	4	2	5	5	3.8
US-97	Siskiyou, CA	4	5	4	3	4	4	4.0
SR-20	Colusa, CA	5	4	3	5	4	3	4.0
US-101	Humboldt, CA	5	3	5	2	5	2	3.7
SR-126	Ventura, CA	4	5	3	4	2	1	3.2

Note: Higher numbers are a better score; each value is from 0-5.

6.1.1. Selected Design Location

The design location selected was US Highway 97 (US-97) in Siskiyou County, California (Figure 24). This section of road is a conventional two-lane highway with one section having a third lane for uphill traffic on the steeper grades near Grassy Summit. Passenger vehicles are the primary user group. Annual average daily traffic (AADT) averages approximately 6,300 vehicles a day. According to traffic demand models, AADT growth is projected to increase five percent per year over the next several years. Additionally, bicyclists use the roadway shoulders, as there are no sidewalks or bike lanes or adjacent bike-ped paths along this route. US-97 is the second most highly used road in Siskiyou County for agricultural and timber product freight and is a popular alternative to Interstate 5 (I-5) because there are fewer steep grades that are difficult for heavily laden freight vehicles to navigate. US-97 is also used as an alternative route when I-5 is closed during winter storms.

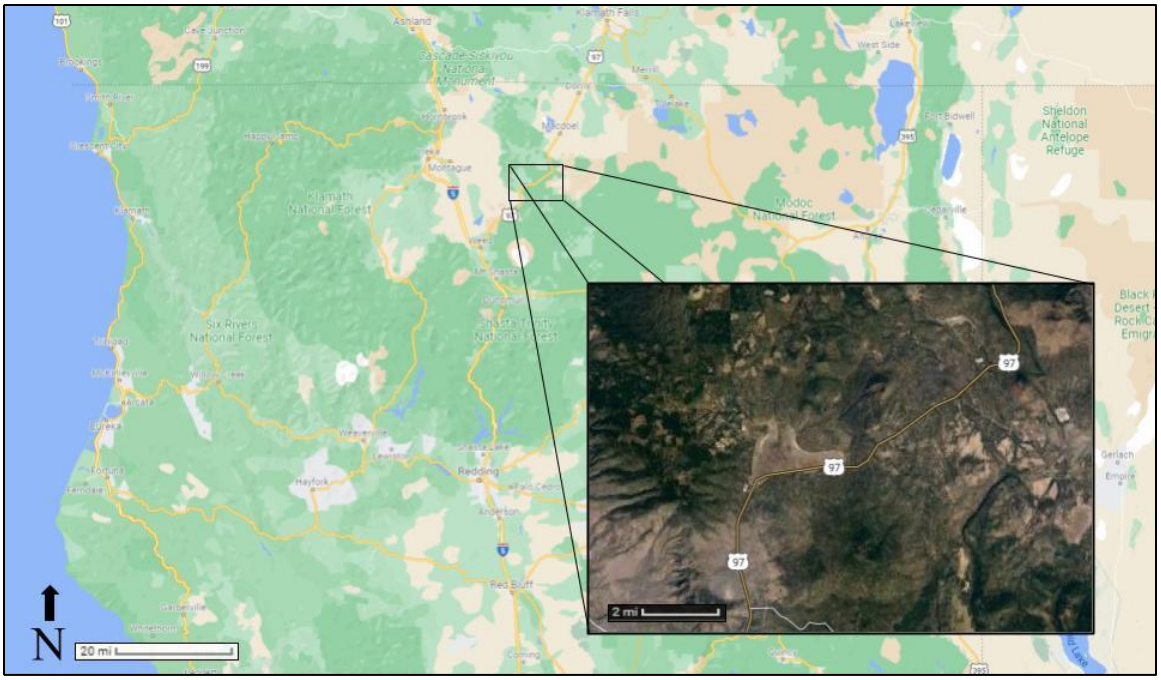

Figure 24: Proposed US-97 mitigation location in Siskiyou County, California.

Caltrans, District 2, identified this section of US-97 as bisecting a priority wildlife corridor and recognized it as an essential ecological connectivity area for this part of California. It also is in the top five percentile for deer-vehicle collision density in recent reports for the entire state of California (Huijser & Begley, 2019).

Based on five years of global position system (GPS) wildlife collar data obtained by the California Department of Fish and Wildlife (CDFW), it was revealed that elk (*Cervus canadensis*) approach the roadway and frequently do not cross (Figure 25). The collar data also identified areas where elk are more likely to cross. The regular movement of large ungulates - elk, mule deer (*Odocoileus hemionus)* and pronghorn antelope (*Antilocapra americana*) - across the roadway create a motorist safety concern in the proposed segment of US-97 requiring mitigation. Caltrans maintenance staff remove 6-7 wildlife carcasses a month from this section of US-97 (W. Stroud, Caltrans, personal communication, 2021). Although wildlife-vehicle collisions are documented along the entire route in the US-97 proposed mitigation segment, there are multiple locations along the road where collisions are more frequent, often referred to as “hot spots”.

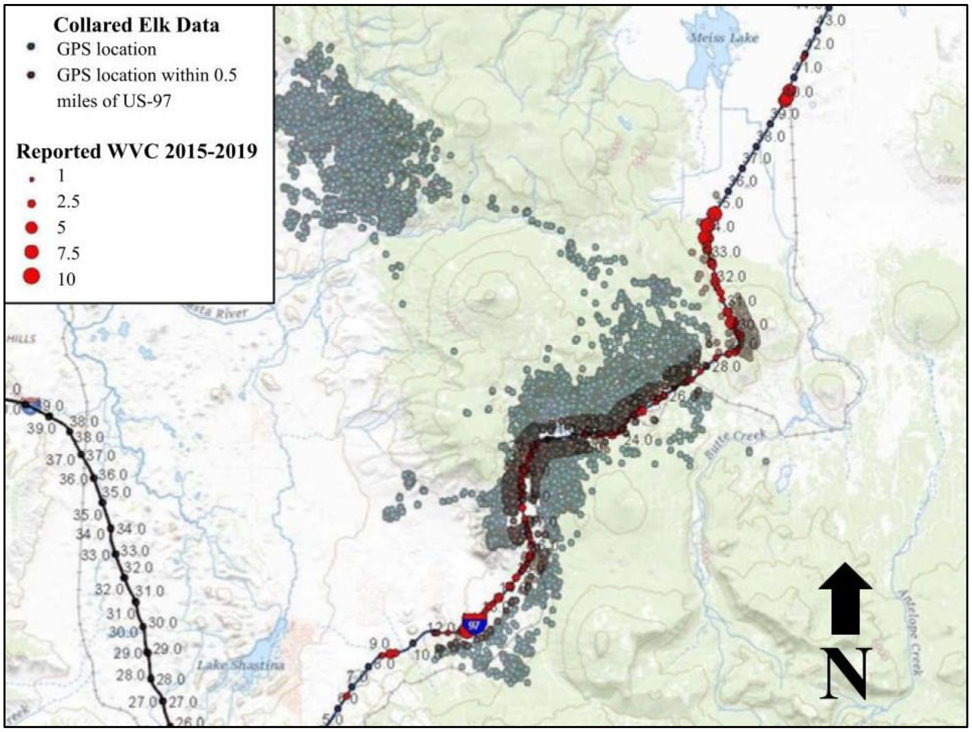

Figure 25: Collared elk GPS locations and WVC density along the US-97 mitigation area 2015-2019.

The high rate of WVCs has led to a heightened concern for public safety and wildlife conservation in this area. As a result, Caltrans and numerous collaborating stakeholders (Siskiyou County Board of Supervisors, the United States Forest Service's Klamath National Forest [USFS-KNF], California Deer Association [CDA], California Highway Patrol [CHP], Rocky Mountain Elk Foundation [RMEF], CDFW, Ore-Cal Resource Conservation and Development Area Council [Ore-Cal RC&D], University of California Davis Road Ecology Center, Fruit Growers Supply Company, and other private landowners) have formed the "State Route 97 Strike Prevention Team" to discuss viable options to reduce WVCs, restore elk/deer migratory corridors, and increase roadway permeability for all wildlife.

6.2. Field Review US-97 Mitigation Segment and Site Selection

Caltrans and CDFW identified six sites, at four locations along US-97 mitigation area that are potentially suitable for a wildlife overpass structure (Figure 26). In July 2020, researchers visited the US-97 location to investigate the potential sites with Caltrans, CDFW, and other local stakeholders. The site visits allowed experts to evaluate roadway, landscape and engineering characteristics that made the site conducive to, or difficult for, designing a wildlife overpass. The different characteristics at each site influenced which FRP bridge solutions were possible for each location. All aspects of the wildlife crossing's design elements (e.g., overpass structure, fencing, jump-outs) were considered during the site evaluations to ensure the selected mitigation site would most effectively improve motorist safety, increase landscape permeability, and support large wildlife migratory corridors as well as other smaller local species movement.

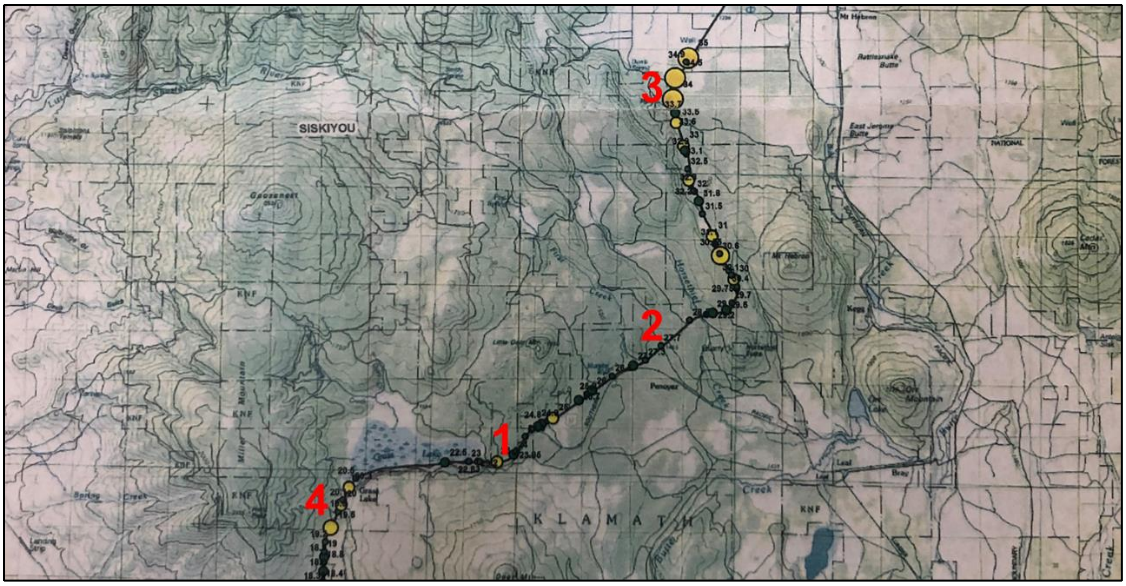

Figure 26: Four locations (bright red numbers) along US Highway 97 identified as potential sites for a FRP wildlife overpass design in Siskiyou County, California.
Note: 1) Grass Lake; 2) Horsethief Creek; 3) Mud Lake; 4) Grass Lake Summit

Topography varies along the US-97 segment, from a mountain pass to wet lakeside habitat. The Grass Lake and Mud Lake areas had two potential sites that were near one another (hundreds of meters apart). Thus, they have the same site name, but are distinguished from one another by either an A or B designation. For additional photos of the design locations, see Appendix C: Additional Photos for the US-97 Mitigation Site.

6.2.1. Location 1: Grass Lake

The Grass Lake site (Site 1 in Figure 26) consists of two locations approximately 100 m (328 ft) apart. In Figure 27, the photo was taken standing on top of Grass Lake 1-A site and is directed towards the Grass Lake 1-B site. They are both on a level, below grade two-lane road with a right-of-way embankment approximately 3 m (10 ft) in elevation at Site 1-A, and 4.5 m (15 ft) at Site 1-B. North and south of the highway is National Forest land. Nearly 100 m (328 ft) south of the road there is a below-grade railroad track that is parallel to the highway. It was determined by the experts review that train traffic could cause issues for the flow of wildlife movement and their approach to a potential crossing structure. There are also access roads near this location that are used by the public and the railroad company. These roads need to remain open, as they provide access points for the public and railroad employees, which could potentially disturb wildlife approaching the crossing site. This site would require gates and cattleguards for the wildlife fencing that directs animals to the crossing and prevents them from entering the roadway.

Figure 27: The Grass Lake mitigation location looking east.

The Grass Lake area is known to support elk and deer movements and is part of the migration route for at least one elk herd. Not unexpectedly, the Grass Lake sites have high levels of WVCs. The Grass Lake 1-B site would be the best option for a wildlife crossing, compared to the 1-A site, due to engineering considerations. The I-B site has 4.5 m (15 ft) high embankments on either side of the road and would require minimal fill for the approach grade. Grass Lake 1-A would require a large amount of fill for the approach to the overpass structure resulting in a costlier design.

6.2.2. Location 2: Horsethief Creek

The second potential site is a two-lane section of US-97 that is below-grade and has an elevation change of approximately 30 m (100 ft) from the top of the hill to the bottom where the road crosses over Horsethief Creek (Figure 28). The change in elevation causes the right-of-way embankments to change in height from 1-6 m (3-20 ft) as the road heads west. The high embankment makes it suitable for an overpass because it would require minimal backfill to build up the approaches. However, there is a gravel road on the north side of US-97 at the start of the Horsethief Creek site that allows public access to National Forest land.

The amount of WVCs in this area are the lowest compared to the other potential sites along US-97. There are very few elk carcasses picked up near here, but deer and other smaller mammals are commonly removed from the road and its verge. This site is part of a mule deer migration route and provides a connection between protected habitat for multiple species, including black bear (*Ursus americanus*).

Figure 28: Horsethief Creek mitigation site looking east.

6.2.3. Location 3: Mud Lake

The Mud Lake location (Site 3 in Figure 26) also consists of two potential sites for a wildlife overpass, and they are located about one-half mile (0.8 kilometer (km)) apart from each other. The Mud Lake A site is the most northern site within the entire US-97 mitigation segment. It has a two-lane, at-grade road that is in the transition zone between forest and grassland habitat (Figure 29). The flatness of the area would require the most fill to create approach ramps to an overpass of all the sites evaluated for this project. This area supports local deer movement and pronghorn antelope are more common here than at the other sites. The Mud Lake A site provides a connection between habitat types for multiple species. The Mud Lake A site has private land on both sides of the highway and would require a conservation easement for the long-term security of wildlife movement if an overpass was to be constructed.

Figure 29: Mud Lake A site looking north.

The Mud Lake B site is south of the Mud Lake A site on US-97 and is within National Forest boundaries. It is in a forested area just beyond the grassland transition zone (Figure 30). The site contains a below grade, two-lane road that traverses the bottom of a hillside. This makes the right-of-way embankment higher on the north side of the road; about 4.5 m (15 ft) on the north side and 3 m (10 ft) on the south. The site supports local deer movement with occasional pronghorn antelope occurring near the road.

Figure 30: Mud Lake B mitigation site looking southeast.

6.2.4. Location 4: Grass Lake Summit

Grass Lake Summit is the most southern of the potential sites in the US-97 mitigation area. At this site the highway is below grade, contains three lanes, and its adjacent embankments are approximately 3.6 m (12 ft) in height (Figure 31). The road traverses a small ridgeline and is located at the highest elevation point at 1,555 m (5,101 ft) within the US-97 mitigation area. Grass Lake Summit is along an established elk and deer migration route as the animals move between their summer and winter ranges. This site has the second most WVCs out of the six potential sites visited in the field review. The land west of the road is owned by the Fruit Growers Supply Company and would require a conservation easement for long-term land use security.

Figure 31: Grass Lake Summit mitigation site looking south-southwest.

6.3. Selected Design Site

After visiting the site, meeting with local stakeholders, and collecting additional relevant data for the US-97 segment, a value matrix was created to contrast and compare each of the six sites by the project's experts. At each site the experts agreed upon the numerical value in each cell of the matrix (Table 7) to serve as a guide in the decision-making process for site selection. Using this guide, the Grass Lake Summit site was selected as the most desirable for the design location for an FRP wildlife overpass. This recommendation was based on the following rationale:

- Grass Lake Summit has the highest conservation value of any of the six sites evaluated.
- Grass Lake Summit had the highest value for addressing WVCs of any of the six sites evaluated.
- There were no identified issues for design and permitting, nor insurmountable conflict issues with landowners or adjacent railroad operations.
- Grass Lake Summit supports the most local and migratory movements of elk and deer.

After reviewing the six sites, and evaluating the various safety, conservation and design criteria, the Grass Lake Summit site emerged as the best location for the FRP crossing design (Table 7). If the crossing structure is designed with adequate lengths of fencing, it could both effectively reduce WVCs for an extended portion of this section of US-97 and improve habitat connectivity.

Table 7: Value matrix for the US-97 FRP design site locations.

Values for Prioritization	US-97 Potential Crossing Sites					
	Grass Lake Summit	Grass Lake (A)	Grass Lake (B)	Horse Thief Creek	Mud Lake (A)	Mud Lake (B)
Safety Criteria						
High EVCs	4	1	1	0	1	1
High DVCs	4	3	3	2	5	5
High WVCs (includes all species)	4	3	3	2	5	5
Safety Values Subtotal	12	7	7	4	11	11
Conservation Criteria						
Elk Migration Route	4	3	2	1	0	0
Mule Deer Migration Route	2	0	0	5	0	0
Supports local deer movement	3	2	2	4	4	4
Supports local elk movement	5	3	3	1	0	0
Connects habitat for multiple spp.	3	3	3	4	4	4
Multiple elk herd use/connectivity	1	1	1	0	0	0
Adjacent conservation improvements	4	3	4	4	4	3
Conservation Values Subtotal	22	15	15	19	12	11
Design and Management Issues						
Archaeological restrictions	4	5	5	5	5	5
Livestock fencing not wildlife friendly	3	3	3	3	3	3
Adjacent railway & ROW management	4	2	3	5	5	5
Wetlands	3	3	3	4	5	5
Adjacent land security (managed for conservation)	3	3	4	5	5	5
Engineering difficulties	3	3	5	5	4	2
Cattle crossing considerations	3	3	3	3	3	3
Adjacent use conflict (i.e., rest stop, access road)	2	2	1	4	4	3
Design and Management Subtotal	25	24	27	34	34	31
Total Value	59	46	49	57	57	53

Note: Higher numbers are a better score; each value is from 0-5.

7. VIRTUAL DESIGN LAB FOR FRP WILDLIFE INFRASTRUCTURE

For this task, project researchers collaborated with the staff of ARC Solutions to convene and host a virtual meeting of experts to discuss potential applications of FRP materials for wildlife crossings. This design component of the project leveraged the experience of a diverse group of professionals to identify potential applications of existing FRP materials in wildlife crossing designs elements, and their likely application at the US-97 site as well as in future FRP crossing projects in North America.

Preceding this project, the first collaborative laboratory (CoLab) was co-hosted by the University of Ryerson's Ecological Design Lab and the Western Transportation Institute in Bozeman, Montana, in 2018. It identified the potential benefits that could be realized by FRP integration into green infrastructure and wildlife crossings and provided a foundation for further exploration of FRP materials in overpass designs for the US-97 site in California.

Modeled after the 2018 CoLab, the original CoLab proposed for this project was to have been an in-person meeting to facilitate interdisciplinary collaboration focused on the integration of expertise from different fields of academic research and agency expertise to solve complex challenges that are outside the realm of any singular discipline. Due to the COVID-19 pandemic and the inability to meet in-person, the CoLab was changed to a virtual design lab (VDL). The goals, methods, and outcomes from this working group are described below.

7.1. FRP Materials Virtual Design Lab

A small working group of experts in wildlife crossings - engineers, landscape architects, and wildlife ecologists - were convened to discuss the potential integration and design of FRP materials in various wildlife crossing elements, other than the bridge infrastructure. A desired outcome was to generate an FRP design guidebook for wildlife crossings that would subsequently be further developed by ARC Solutions. The guidebook will 1) provide Caltrans with site-specific uses of FRP materials that would help ensure a buildable, effective, and context-sensitive design for the site along US-97; and 2) identify and evaluate opportunities for general integration of FRP materials into various design elements for future FRP wildlife crossing infrastructure in other locales across North America.

Three discussions with workshop participants were hosted on Zoom™, with additional electronic communication and correspondence supported throughout the planning and design process. For the three key discussions, participants collaborated in real time using Google Jamboard™. Google Jamboard™ is a collaborative interface used to facilitate online workshop participation. It can be thought of as a shared virtual whiteboard that allows the group to collaboratively record, share, and organize comments in real-time.

7.1.1. Participants

An interdisciplinary team of wildlife crossing experts was convened by ARC Solutions, with the guidance of Caltrans, to identify key individuals and stakeholders to involve in the decision-making process for the US-97 crossing site.

7.1.1.1. Engineering Working Group Participants

- Robert Ament, Western Transportation Institute - Montana State University (WTI)
- Matthew Bell, Research Engineer, WTI
- Marta Brocki, Associate Director, ARC Solutions
- Renee Callahan, Executive Director, ARC Solutions
- Damon Fick, Structural Engineer, Senior Research Engineer, WTI
- Manode Kodsuntie, Bridge Design, Caltrans
- Heidi Kuntz, Structure Maintenance Investigations Senior, Caltrans
- Terry McGuire, Professional Engineer, Consultant, Parks Canada Agency (ret.)
- Robert Rock, Principal and Landscape Architect, Living Habitats
- Ryan Stiltz, Technical Liaison Engineer, Caltrans

7.1.1.2. Landscape Working Group Participants

- Robert Ament, Road Ecology Program Manager, WTI
- Matthew Bell, Research Engineer, WTI
- Marta Brocki, Associate Director, ARC Solutions
- Renee Callahan, Executive Director, ARC Solutions
- Marcel Huijser, Wildlife Ecologist, WTI
- Sandra Jacobson, Wildlife Biologist, United States Forest Service (retired)
- Richard Lis, Senior Environmental Specialist, California Department of Fish and Wildlife
- Nina-Marie Lister, Professor, Ryerson University; Director, Ecological Design Lab
- Robert Rock, Principal and Landscape Architect, Living Habitats
- Eric Rulison, Biologist, Caltrans
- Robin Solari, Landscape Architect, Caltrans

7.2. FRP Materials Virtual Design Lab Categories

The exploration of potential uses of FRP materials that were evaluated during the VDL were divided into three categories: basic, enhanced, and innovative. Below is a summary of these categories and the FRP wildlife infrastructure elements were placed in. These groups made it easier to identify applicable solutions and areas where more research is required.

Basic**:** Solutions identified within this category include FRP applications that are developed, tested, and can be implemented along the North American road network. They are a readily available technology that use conventional construction methods and require minimal departure from existing agency practices.

Enhanced**:** This category included modifications to the wildlife crossing design that provide opportunities to integrate FRP in novel ways that leverage and demonstrate the material's positive qualities, enhance the ecological and structural function of the crossing, or provide ancillary benefits in the form of interpretive components. These applications may require additional agency approval or veer from traditional construction methods.

Innovative: Applications of FRP categorized as innovative require additional research prior to their integration into a wildlife crossing design. They have been identified as needing further investigation based on their potential to deliver benefits in structural design, feasibility, sustainability, or ecological function.

7.3. Results of the Virtual Design Lab

The FRP guideline document that summarizes the design recommendations for the various applications of FRP materials for wildlife crossings will be available at a later date, upon its completion by ARC Solutions. Preliminary results from the VDL are described in Appendix D: Summary of Preliminary Virtual Design Lab Results.

8. FRP OVERPASS DESIGN FOR GRASS LAKE SUMMIT ALONG US-97

Based on information gathered from the previous tasks, the experience of Caltrans personnel and the selected FRP manufacturer, a preliminary design for the overpass was completed for the selected Grass Lake Summit site on US-97. The design includes FRP bridge members and related wildlife crossing design elements (e.g., fence, sound/light barrier, jump-outs) required to make an effective and safe wildlife crossing. The purpose of the designs for these FRP components is to provide a resource for the successful planning and completion of wildlife overpass within the framework of established construction planning and the Caltrans bridge approval process. The improvements and comments are based on the preliminary mitigation site plans provided by Caltrans and in no way reflect a completed or approved design.

The primary objective for the US-97 site is to reduce the high number of WVCs while also providing for habitat connectivity. The majority of WVCs in the Grass Lake Summit area involve elk or deer and therefore are the focal species for the wildlife crossing design. Design considerations (e.g., the percent slope of the approach to the crossing structure, fencing) were prioritized to facilitate their effectiveness for these two native ungulates.

Based on camera trap data collected by CDFW, the presence of the following animals has also been confirmed at, or near, the crossing site: grey wolf (*Canis lupus*), cougar (*Puma concolor*), black bear (*Ursus americanus*), and smaller mammals such as rabbits, gophers, voles, mice, and squirrels. The design elements described below, include the landscaping, overpass structure, and fencing, seek to address the needs of these species as well.

8.1. Bridge Geometry

This wildlife overpass along US-97 was designed to span three lanes of traffic, each lane is 3.7 m (12 ft) wide. The span includes two shoulders on either side of the three lanes, consisting of 9.1 m (3 ft) of asphalt and 2.4 m (8 ft) of unpaved landscape. The overall road width of 17.7 m (58 ft) under the overpass is shown in Figure 32. The edge of the asphalt transitions to an upward sloped section to the abutments allowing Caltrans space to conduct below deck maintenance inspections. The design clearance height for the bridge is 5.3 m (17.5 ft), which provides an additional 30 cm (1 ft) of structure clearance for highway bridges designed in the U.S. Caltrans engineers opted for the additional clearance height to reduce the likelihood of a vehicle impact on the FRP structure, given its specialty repair procedures that would be required in the event of an overhead strike. Using the typical Caltrans standards for horizontal clearance and slope to the abutments, a bridge span of 35 m (115 ft) was selected with guidance from Caltrans structural engineers. An elevation view of the bridge span and clearance envelope can be seen in Figure 32.

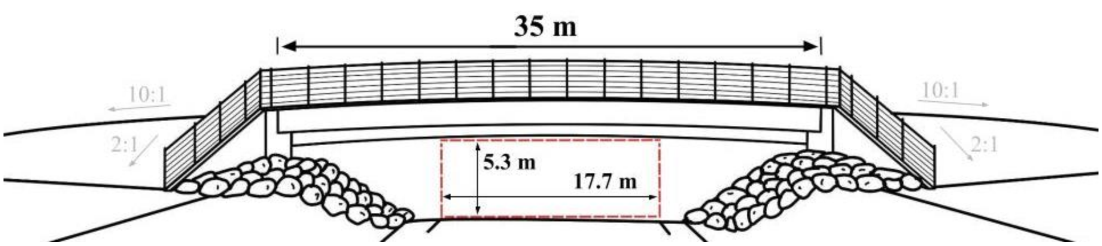

Figure 32: Elevation view of the US-97 wildlife overpass.

The below-grade road characteristic at Grass Lake Summit makes the adjacent soil grades on each side of the highway suitable for minimizing the fill required for the approaching slope to the structure. A slope that is less than 20% (5:1) is sufficient for an elk crossing, but a flatter approach closer to 10% (10:1) is recommended to provides ample visibility across the structure for elk and deer. In addition to the approach slope's grade, the recommended crossing width for large wildlife, such as elk, is 50 m (164 ft).

A plan view of the wildlife overpass can be seen in Figure 33, with an aerial representation of the bridge footprint in
Figure 34, showing the estimated placement and footprint at Grass Lake Summit.

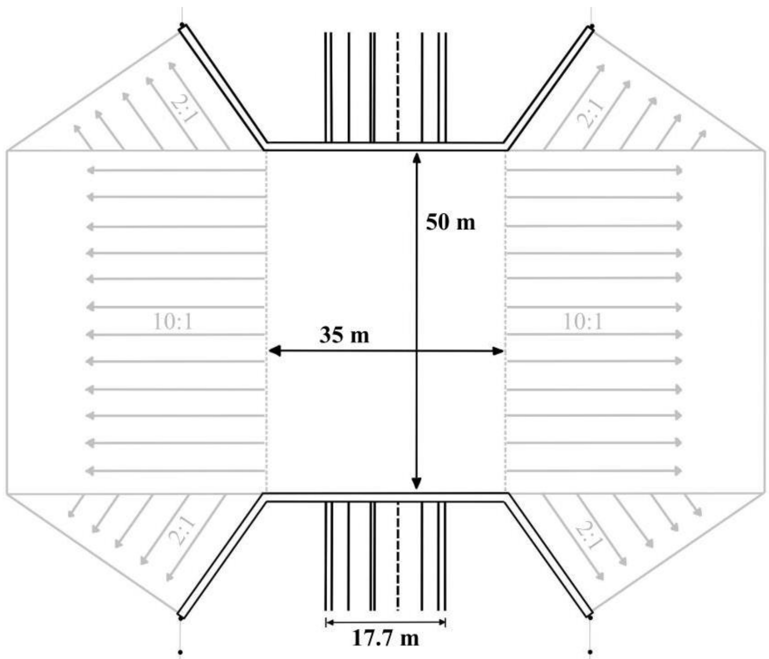

Figure 33: Plan view with dimensions of the US-97 wildlife overpass.

Figure 34: Aerial representation of the US-97 FRP wildlife overpass footprint.

Note: The map base layer was taken from Google Earth. Although the surrounding area looks like short brush, they are pine trees and do not represent the true height relative to the crossing structure.

8.2. Landscaping Design

The type of landscape required on top of the overpass is dependent on the target species and is intended to support their use of the structure by providing vegetation similar to adjacent habitat. For the target species, elk, open grassy habitat is sufficient. Other, smaller species, or less mobile species, may benefit from hiding and thermal cover provided by woody shrubs, piles of rocks, downed logs, and other types of materials that break up the openness of the crossing. Thus, heterogeneity of habitat structure, or plant community physiognomy, ensures that species that avoid, or are vulnerable in, openings are considered in the landscape design. Therefore, the overpass structure's landscaping should include a combination of open grassy spaces intermixed with various woody vegetation and physically complex areas, such as rock piles.

8.2.1. Surface Aggregates and Vegetation

To accommodate elk and deer use of the structure, the landscape design should include a combination of native grasses, forbs and shrubs that provide a rich mix of species. The lack of knowledge related to the relationship of animals with artificial landscape materials (e.g., tire piles, FRP members, small water guzzlers) has created an emphasis on the use of natural materials. Thus, native materials that provide hiding cover for small animals (e.g., logs, rocks, tree limbs, root wads) and native vegetation and plant species are recommended for this overpass.

Native seed mixes using local genotypes are recommended to establish vigorous native plants to help to reduce the encroachment of exotic, invasive species on or adjacent to the crossing structure. A short list of some desirable trees, shrubs, forbs and grasses naturally occurring in this area of the Cascade Mountains (Table 8) could be used on top of the overpass and to rehabilitate adjacent disturbed area from construction. The list is illustrative and not exhaustive. Special attention should be paid to select species that are adapted to the drier more xeric habitats of the area.

Further exploration of whether local ecotypes of these and other native species used for revegetation are commercially available would be necessary. To assure local ecotypes are used, seeds or vegetative cuttings could be harvested from native plants at, or near, the crossing site. The collected seeds and cuttings could then be used by a local landscape nursery to grow, multiply and harvest plants for restocking the disturbed areas of the crossing site.

A design consideration for wildlife bridges is the longitudinal slope of the structure to prevent the ponding of water on the bridge. Efficient water movement will be accommodated through the design of an appropriate camber in the FRP super structure, creating a visible, shallow arched appearance from the roadway. A waterproof membrane should be placed over the entire concrete deck before applying the surface substrate. Perforated pipes, 10 cm (4 in) in diameter, placed in the longitudinal direction of the crossing structure should be placed at the bottom of the gravel substrate and eventually be exposed at the ends of the bridge. At both ends of the structure, the exposed portion of the drainage pipes should then be covered with a 20 cm (8 in.) layer of granular material 3-6 cm (1-2 in) diameter in size, to collect the excess water. A landscape fabric will be placed over the gravel to prevent settling of the organic soil layer into the granular base, but still allow water to penetrate through the fabric.

The depth of the soil required on an overpass is dependent on the species and the physiognomy of the vegetation – its structure, appearance, canopy cover – selected for the landscaping. Approximately 76 cm (30 in) of topsoil should then be applied to accommodate low growing shrubs and other native plant species identified in Table 8. The slight grade provided by the superstructure camber will allow for the natural flow of surface water from the center of the overpass to the ends of the bridge and ultimately into the soil subsurface adjacent to the structure.

Table 8: A short list of native species that could be used to reclaim US-97 wildlife overpass site that are present in adjacent habitats.

Scientific Name	Common Name
Trees	
Pinus contorta	Lodgepole pine
Pinus ponderosa	Ponderosa pine
Shrubs	
Artemesia tridentata	Big sagebrush
Chrysothamnus viscidiflorus	Green rabbitbrush
Purshia tridentata	Antelope bitterbrush
Ribes cereum	Wax currant
Symphoricarpos albus	Common snowberry
Arctostaphylos patula	Greenleaf manzanita
Forbs	
Antennaria microphylla	Littleleaf pussytoes
Arnica cordifolia	Heartleaf arnica
Balsamorhiza sagittata	Arrowleaf balsamroot
Cornus canadensis	Bunchberry dogwood
Fragaria virginiana	Strawberry
Lupinus spp.	Lupine species
Grasses	
Festuca idahoensis	Idaho fescue
Poa sandbergii	Sandberg bluegrass
Pseudoroegneria spicata	Bluebunch wheatgrass
Sitanion hysterix	Squirreltail
Stipa occidentalis	Western needlegrass

8.2.2. Habitat Planting Strategy for Crossing Structure

A relatively low-density dry coniferous forest surrounds the crossing site on both sides of the highway. The forest canopy is dominated by ponderosa pine (*Pinus ponderosa*). The open grown single layer coniferous forest has a few scattered understory trees combined with a relatively sparse mix of woody shrubs, herbs and grasses (Figure 31). The vegetation grows on a substrate of volcanic deposits – ash, pumice, tephra – that have sporadically occurred in the region for millennia, as well as rhyolitic and andesitic flows (Simpson, 2007). The local landscape also contains a mix of rocks and boulders that naturally occur throughout the area.

For the crossing structure, the creation of habitat with zones that accommodate the movement preferences of a range of smaller mammal species as well as elk and deer through a semi-vegetated landscape was the recommended strategy of the ARC Solutions CoLab and is shown in Figure 35. Combined, there are three different parallel bands that provide a variety of habitats and hiding cover needs for the diverse wildlife species that potentially will use the structure. It is recommended to use locally sourced logs and volcanic rocks. These rocks are lighter than other types of rocks derived from granite or other metamorphic sources and reduce loading of the structure. The dark volcanic rocks also blend nicely with the surrounding landscape and black recycled-plastic FRP used for the sound/light barriers and fencing. The plants selected should be those that are best suited for a xeriscape to reduce the need to retain water on the structure.

At each end of the overpass, along the barrier walls, a gravel path should be created where no vegetation is planted. This will allow maintenance personnel to easily access the sound and light barrier along the side of the structure for inspection, maintenance, or repairs. Along the north side of the crossing would be continuous shrub/grass/herb cover for smaller, low mobility species. This band of cover is 9.1-12.2 m (30-40 ft) wide and provides continuous cover so smaller animals are not exposed to any large openings as they cross the structure. The center habitat band of the crossing is a 24.4-30.5 m (80-100 ft) wide area seeded with low growing grasses. This area will provide clear visibility across the entire structure for elk and deer. There are minimal obstacles to interfere with animal passage. On the south side of the are clusters of hiding cover provided by logs, volcanic rocks, and scattered shrubs. This allows species the ability to jump between the covered areas as they cross, to rest or feel secure (e.g., from birds of prey). Combined, the crossing's vegetative design offers species with varying needs, a mix of habitat in three different avenues or zones of passage: 1) a continuous woody shrub dominated area, 2) an open grassy central area designed for the two focal species, deer, and elk, as well as other large mammals; and 3) a band of varying habitat islands – low growing vegetation, shrubs, logs and rock piles. A representation of this landscaping strategy can be seen in Figure 35.

For the approaching slopes to the crossing structure, deeper soils of 1 m (3.3 ft) or more could be used to replace ponderosa pine trees in the disturbed footprint from construction. This would keep the gap in the forest overstory canopy to a minimum. Based on the field review of the site, breaks in the ponderosa pine forest's canopy equal to the 35 m (115 ft) span of the overpass commonly occur throughout the surrounding area.

8.2.2.1. Summary of Landscape Recommendations

Below is a brief overview of the landscape design recommendations for the wildlife crossing:

- Maximum of 20 cm (8 in.) granular drainage material, plus 76 cm (30 in.) of organic soil, for a total of 97 cm (38 in.) material on top of the structure.
- Camber in the structural girders to facilitate water drainage off the crossing structure to the surrounding subsurface soils.
- The landscaping for the crossing structure will include a large central open area covered with native grasses to facilitate elk movement.

- Continuous areas and islands of hiding cover will be provided via woody shrubs, rock piles, root wads and other native materials for smaller animals.
- Local ecotypes of native plants – trees, shrubs, forbs, grasses – should be used for vegetating the site.
- Locally sourced volcanic rocks and woody debris will be used for small mammal habitat.

Figure 35: Planting strategy with clear path of visibility through the center of the structure.

8.3. Overpass Structure

With knowledge of the target species crossing behavior and the extent of soil, drainage, and landscaping features, a preliminary design of the FRP elements of the wildlife overpass was completed. The design utilizes recommended crossing geometry and loading to create a feasible FRP tub girder cross section with a composite concrete deck that meets the objectives of the US-97 site.

8.3.1. Overpass Loading

Working with Caltrans structural engineers, service loads and load combinations were developed for the preliminary design of the crossing superstructure. Loads considered were self-weight, superimposed dead loads, and vehicle, animal, and snow live loads. Recommended loads are provided in Table 9 and briefly summarized below.

Table 9: Design Load Summary

Element	Unit Weight (kg/m^3)	Dimension	Loads Concentrated (kg)	Loads Line (kg/m)	Loads Uniform (kg/m^2)	Reference
Pervious drainage fill	1,602	20 cm	-	-	327	-
Earth fill (lightly compacted)	1,602	76 cm	-	-	1,465	-
Vegetation	-	-	-	-	24	-
FRP tub girder	-	2.3 m spacing	-	164	78	-
Precast concrete form	2,403	8 cm	-	-	186	-
Cast in place concrete	2,403	10 cm	-	-	244	-
Concrete soil curb	2,403	1.1 m tall	-	164	156	-
FRP sound and light barrier	961	2.4 m	-	104	98	-
H-10 Truck loading	-	-	9,072	-	171	(AASHTO, 2014)
Elk		10 cm x 10 cm	454	-	171	-
Livestock	-	-	-	-	488	(Pedersen et al., 1983)
Equestrian		10 cm x 10 cm	454	-	171	(AASHTO, 2009)
Pedestrian load	-	-	-	-	439	(AASHTO, 2009)
Snow (strength limit state)	-	-	-	-	610	Caltrans
Snow (extreme event)	-	-	-	-	781	Caltrans

The self-weight of the structure includes a uniformly distributed load of 78.1 kg/m^2 (16 psf) for the FRP tub girder, an 8 cm (3 in.) precast concrete form of 186 kg/m^2 (38 psf), and a 10 cm (4 in.) cast-in-place concrete deck weighing 244 kg/m^2 (50 psf). Precast and cast-in-place concrete will use FRP rebar instead of carbon-steel to eliminate the corrosion potential and increase the service life of the overpass.

Superimposed soil dead loads assume a partially compacted unit weight of 1600 kg/m^3 (100 pcf) for the granular drainage and organic soil loading. This value represents an average of the unit weight of traditional compacted soil 1920 kg/m^3 (120 pcf) and engineered growth media from commercial sources 1120 kg/m^3 (70 pcf). For a total soil thickness of 97 cm (38 in), the distributed load is 1860 kg/m^2 (380 psf). An additional superimposed dead load of 24 kg/m^2 (5 psf) was included to account for larger, individual plants or cover objects that may be dispersed along the crossing structure’s length. For the two girders on the outside of the crossing, additional dead loads for a 1.1 m (44 in.) tall concrete curb weighing 165 kg/m (110 lb/ft) and a 2.4 m (8 ft) tall recycled plastic FRP sound/noise barrier at 104 kg/m (70 lb/ft) were included. Distributing these loads to a single girder on the outside of the crossing results in loads of 156 kg/m^2 (32 psf) and 98 kg/m^2 (20 psf) for the curb and barrier, respectively.

The overpass structure was considered a pedestrian bridge for vehicle and animal live loads. A single lane of an H10 design vehicle (two-axle truck weighing 9,100 kg [20,000 lbs]) or approximately 171 kg/m^2 (35 psf) was used without a lane load; this assumed that multiple vehicles would not be on the bridge at one time. It was also assumed that construction equipment used to place and distribute the soil and vegetation on the bridge will not exceed a single lane of an H-10 design truck. Elk loading on the bridge was treated as an equestrian concentrated hoof load of 450 kg (1,000 lbs) for the concrete deck design. The distributed load for a herd of elk crossing two-wide over a 2.3 m (7.5 ft) tributary tub girder spacing was assumed to be 170 kg/m^2 (35 psf).

The US-97 crossing location is in a site-specific area for determining snow loads, mostly for non-transportation structures. Based on the assumption that snow removal will not occur on the wildlife overpass, a 50-year accumulation event (ASCE, 2017) was used to determine a snow load of 610 kg/m^2 (125 psf). This load is specified by the Siskiyou County building department for the design of building roofs and other structures. An extreme snow event loading of 780 kg/m^2 (160 psf) was also considered for the overpass structure because an accumulated snow load of nearly 4.9 m (16 ft) occurred in 1959 within 32 km (20 miles) of the crossing location.

A deflection limit of $L/600$ (L = bridge length in inches) was used to select the height or depth of the girders. This is the same deflection limit used for highway bridges and accounts for vibration and driver perception from heavy and dynamic truck loading. A larger bridge deflection limit may be reasonable for wildlife crossings, however the more stringent limit for highway structures was used due to the lack of understanding of wildlife's perception and tolerance of vibration.

8.3.2. FRP Superstructure

The FRP system selected for the crossing superstructure is a composite tub (CT) girder designed and manufactured by Advanced Infrastructure Technologies (AIT). The CT girder system consists of lightweight FRP tub girders that are supported on standard foundations with precast panels or cast-in-place concrete providing the deck surface. A previously constructed bridge using AIT's CT girders can be seen in Figure 36. The first CT girder bridge was constructed in 2020 in Maine. AIT is currently working on additional bridge designs for Maine, New Hampshire, and Florida DOTs, with spans ranging up to 32 m (105 ft) in length.

The estimated cross-sectional dimensions of the CT girder for the US-97 wildlife overpass are shown in Figure 37. For an overall crossing width of 50 m (164 ft) and a girder spacing of 2.3 m (7.5 ft), 22 girders with an approximate depth of a 142 cm (4.7 ft) will be used. These dimensions were estimated by AIT, with their proprietary software, to calculate dimensions of the girder and the number of fiber-matrix layers required for each structural plane. An estimated design load of 2,441 kg/m^2 (500 psf) was given to AIT based on the analysis used to create Table 9. The dimensions shown in Figure 37 are approximate estimates to the size of the CT girder required for the US-97 wildlife overpass.

Figure 36: The CT girder bridge system installed during first construction in Hampden, Maine, 2020 (Advanced Infrastructure Technologies, 2020).

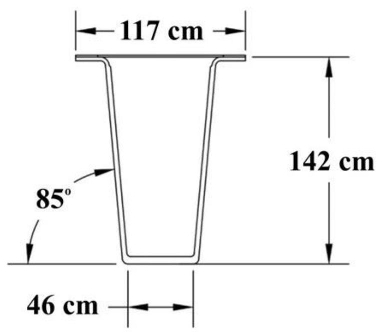

Figure 37: Cross section of the preliminary design for the CT girder from AIT Bridges.

The method of constructing the CT girder bridge is described below, using Figure 38 as a reference to the associated wildlife bridge elements. To assist with accelerated construction, a 75 mm (3 in.) precast concrete panel, B (Figure 38), is attached to two tub girders, A. FRP rebar will eliminate corrosion in the reinforcement of the decking and is predicted to help minimize maintenance. The J-shaped FRP through-bolts on the sides of the CT girder flanges provide the connection required for composite action between the girder and concrete panel, C in Figure 38. This two - CT girder assembly unit is placed on top of the abutments and reduces the number of lifts, contributing to a more efficient construction process than a similar sequence for heavier steel and concrete girder bridge construction. In addition to faster girder installation, the precast concrete panel on top of the 2-CT girder assembly provides the formwork for a full-depth cast-in-place concrete deck.

After all the 2-girder assembly units are in place, the precast concrete panels are connected by longitudinal concrete closure joints, D in Figure 38. The precast concrete surface provides the formwork for the additional 4 in. cast-in-place reinforced concrete deck, E in Figure 38. The cast-in-place deck also uses FRP rebar. The connection between the precast and cast-in-place concrete is provided by the same FRP J-shaped anchors that pass through the precast member, C in Figure 38. An intentionally roughened surface on the top of the precast panels provides the additional shear connection for composite action between the cast-in-place concrete and precast concrete. The FRP J-bolts contribute to a corrosion-free structural assembly. Along each side of the bridge, a concrete curb, F in Figure 38, with FRP rebar is constructed on top of the completed deck to retain the soil on the structure and support the recycled plastic FRP sound and light barrier, J in Figure 38.

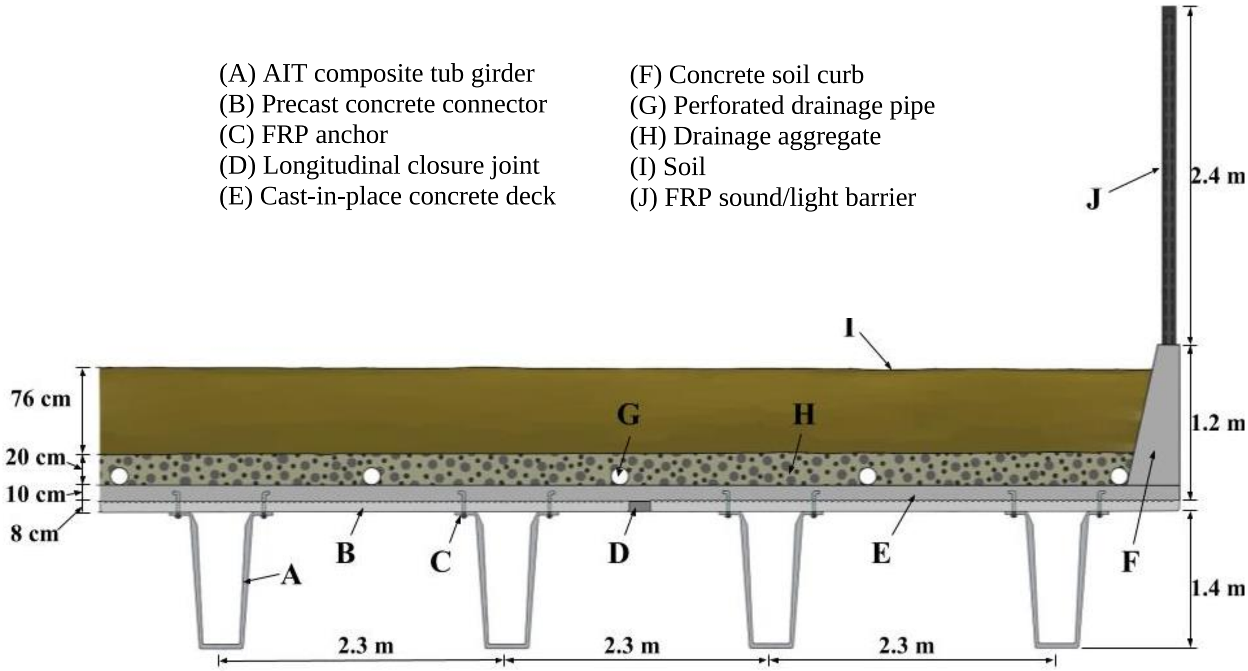

Figure 38: Cross section of the wildlife overpass showing the layout of the girders, concrete deck, soil, drainage, and barriers on the bridge span.
Note: Image not drawn to scale.

8.3.3. Sound and light barriers

There are many alternatives for providing an FRP sound and light retaining barrier along the edges of a wildlife overpass. Variations include cantilevered hollow tube posts to attach barrier elements or prefabricated FRP panels that can be installed quickly and directly to the concrete curb. Many of the available products are not labeled or marketed specifically as a sound-reducing member. Therefore, additional investigation into their effectiveness at reducing the decibels at various wavelengths was pursued.

It is recommended that a simple recycled plastic FRP light and noise barrier resembling a traditional wooden fence be used on both sides of the structure (Figure 39). The density of the FRP boards was estimated to be from 720-960 kg/m^3 (45-60 pcf). The FRP boards using recycled plastic are denser than traditional wood fencing and are predicted to significantly reduce the sound from passing vehicles below when compared to a wood fence. This will also eliminate light and reflected light from vehicle headlights and running lights from the line-of-sight of animals while they are on the overpass. The barrier design shown in Figure 39 uses recycled plastic FRP posts that have an I-beam cross-section; they are connected to the top of the soil-retaining concrete curb along the edge of the overpass. The I-shape enables FRP boards to slide quickly into the horizontal position, held in place by the I-shaped flanges.

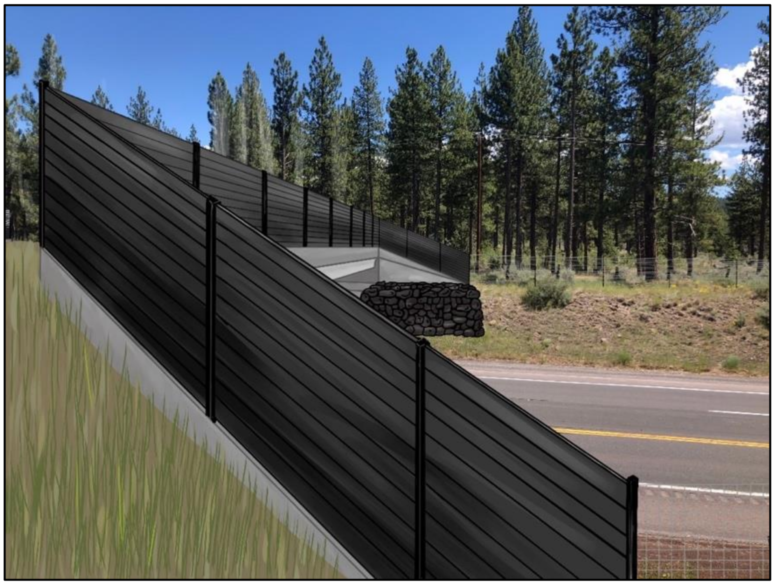

Figure 39: Recycled-plastic sound and light barrier installed on top of soil-retaining concrete curb.

Figure 40: Rendering of US-97 FRP wildlife overpass with Mt. Shasta in the background.

8.4. Wildlife Fencing and Supporting Elements

Wildlife overpasses and underpasses with fencing, are proven to significantly reduce WVCs with large animals, while at the same time provide safe crossing opportunities for many species of varying size. An overpass, without fencing, is often less effective or ineffective at reducing WVCs (Huijser et al., 2016). It is recommended that a minimum of 5 km (3 mi) of fencing be erected to reduce collisions with large wildlife at the US-97 wildlife crossing site. The fence ends that are furthest from the crossing structure should be designed to direct animals away from the road or be tied into existing fencing or landscape features.

For the US-97 site, it is recommended to use recycled plastic FRP posts and pultruded lumber instead of wood or steel for the wildlife fencing elements (e.g., gates, jump-outs). Wildlife fencing made with FRP posts uses the same construction techniques as conventional steel and wood wire-mesh fences. Fence posts can either be driven into the ground for straight sections of fencing or placed in a concrete base with bracing for additional support at corners, slope changes and turns. Recycled plastic is recommended for fencing elements because they will last longer than traditional materials, remove landfill waste, and can be recycled if sections of the fence need to be replaced. A rendering of the recycled plastic fencing elements can be seen in Figure 41.

Road access points through the wildlife fencing along the US-97 mitigation area should be minimized to reduce potential points for animals to breach the fencing and enter the roadway. Each access location should be addressed individually with the appropriate mitigation method (e.g., cattle guard, gate, electric mat) and will be influenced by land ownership and public use requirements. Wildlife jump-outs, such as the example shown on the right side of the fencing Figure 41, should be placed along the fence every 0.5-0.8 km (0.3-0.5 mi), with additional jump-outs added near road access points and areas where animals are more likely to be on the highway side of the fencing.

Figure 41: Representation of recycled-plastic posts for use in wildlife fencing, gates, and jump-outs.

8.5. Adapting US-97 Design for Bicycles and Pedestrians

The wildlife overpass design for US-97 is in a rural area and has been identified as a major wildlife corridor in Northern California. The purpose of the structure is to reduce WVCs and increase, or maintain, wildlife connectivity. It is not recommended that the US-97 wildlife overpass be designed as a multiuse structure. Although, some small- to medium-sized animals (e.g., fox coyote, raccoons, skunks, etc.) are capable of adapting to multiuse structures, animals found in the area of the US-97 location (e.g., wolves, cougar, and elk), are more sensitive to human activities and may be deterred from using the overpass if it is established as a multiuse structure. Roads should not be on or near wildlife overpasses and the structure should be closed to all types of human-use activities (Beckman et al., 2010). It is recommended that multiuse wildlife crossing structures only be used in or near urban areas, where the purpose of the structure is to pass both humans and wildlife safely across a busy highway.

8.5.1. Multiuse Wildlife Crossing Considerations

If a wildlife overpass is designed to accommodate pedestrians, there are two common types of structures that can be designed. First, is an open path that is a designated trail over the crossing with no barrier between the walking path and the vegetation on top of the bridge. This type of pedestrian crossing will allow people to use all areas of the crossing, the same as wildlife. The second type is to provide pedestrians a designated path that is separate from the vegetated habitat as shown in Figure 42. This method can only be used if the start of the walking path over the wildlife structure starts on the roadway side of the exclusionary fencing. This means that animals will not be able to access the walking path unless they are already walking along the roadway. If the walking path barrier starts on the wildlife side of the exclusionary fencing animals will be able to cross it freely, increasing the likelihood of a human-animal interaction on a narrow walking path.

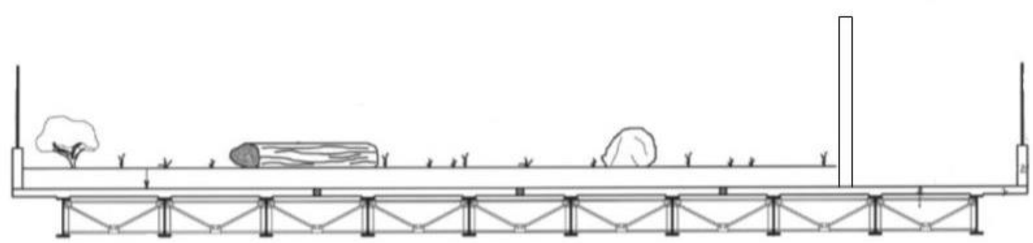

Figure 42: Cross section of wildlife overpass with divided pedestrian walking path on the right side.

8.5.2. Using the US-97 FRP Technology for a Multiuse Structure

Although there have been many applications of FRP pedestrian bridges, the CT girder system used for the US-97 wildlife crossing design has yet to be used for a pedestrian bridge. This system is an ideal candidate for this type of bridge due to its ability to be installed quickly. It is possible to build and entire bridge and install it quickly with just one crane lift.

The strength of the CT girders makes it possible to build any size pedestrian bridge desired. This design uses two CT girders for the superstructure (Figure 43). One girder is also possible but will be more susceptible to rotational forces. Rather than connecting a pre-cast concrete deck to the girders, an FRP deck can be attached to reduce the weight. It is also possible to use recycled plastic for the railing along the pedestrian bridge.

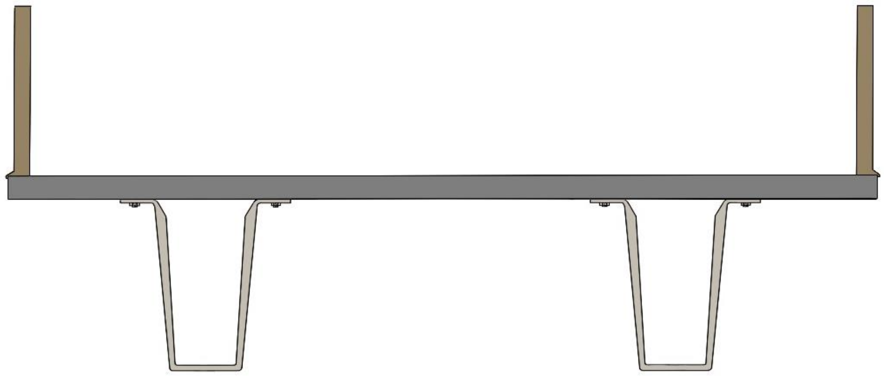

Figure 43: Cross section of CT girder pedestrian bridge design.

9. LIFE CYCLE COST ANALYSIS

The life-cycle costs and benefits of using FRP for wildlife crossing infrastructure and associated design elements were estimated and compared with traditional construction materials (e.g., wood, concrete, steel). The use of FRP materials is becoming more prevalent in infrastructure projects due to their high strength-to-weight ratio, suitability for accelerated construction, minimal maintenance, and 100-year service-life (Kim, 2019). Current FRP research and development suggests that bio-based fibers and recycled plastics will be able to replace virgin polymer materials in the future – making FRP structures even more desirable and sustainable options (Gkaidatzis, 2014; Wool & Sun, 2011).

The benefits of using FRP materials has not been fully realized due to their relatively recent use in infrastructure construction. The advancement of FRP technology has improved greatly since the first FRP bridges were built in the 1990s and it is now common for manufacturers to offer 50-year warranties based on their confidence in reaching a 100-year service life. Expectations for the longevity of FRP reinforcement has also been exceeded based on research and performance investigations (Ramanathan et al., 2021). In addition, FRP materials are now commonly made with fire and ultra-violet additives that make them more resistant to environmental degradation than the original FRP materials developed over a generation ago.

A cost-benefit analysis (CBA) is an effective way to compare the estimated costs associated with engineering designs, but typically, does not capture the entire service life of long-lived structures and/or materials. CBAs produce more reliable results for projects with shorter time horizons where expenses are easier to quantify. This characterization is supported by published literature documenting the more appropriate life-cycle cost (LCC) analysis approach for structures with longer expected service life. LCC analyses considers expenses of structures over long time periods and assesses the costs associated with maintenance, reconstruction, and end-of-life disposal. The long service life of FRP materials balances their initial higher material costs (than concrete and steel) with their superior durability.

One inherent challenge in evaluating the LCC of bridges made from FRP materials and more specifically, a wildlife overpass, is the unknown deterioration caused by the landscape and wildlife compared to exposed pavements and highway traffic. For the purpose of this evaluation, only the costs related to FRP composite girders used in the preliminary design for the US-97 site is considered. In some cases, cost estimates have been interpolated or extrapolated to more accurately represent the unique and specific geometry of the FRP overpass structure considered in this project. The concrete and steel bridge cost estimates are based on actual bridge construction cost data, published by Caltrans. This approach is intended to create a reasonable comparison of three similar bridge types where the main difference is the material used for the overpass superstructure (e.g., concrete, steel, FRP). An LCC analysis is also conducted for the wildlife fencing, in particular the posts used for fences (e.g., wood, steel, or FRP).

9.1. Review of Recent FRP LCC Analyses

The following information summarizes published case studies and LCC analyses that were used to establish potential costs and benefits associated with FRP materials for a wildlife overpass and fencing elements along US-97. Conclusions presented in this section are specific to the conditions where the research was performed and may not directly apply to the design site on US-97. They do, however, provide FRP cost data that is used as a baseline in this research to improve the LCC analysis results for a specific FRP bridge and geometry for which no data is available.

9.1.1. Quantifying the Impact of FRP for Improved Resistance

A LCC analyses estimated the financial and environmental impacts of AIT's CT girder compared with prestressed concrete girders reinforced with carbon-steel or stainless-steel bars for a bridge replacement in St. Petersburg, Florida (Wozniak, 2021). The bridge used in the analysis was a two-span bridge with a total length of 29 m (95 ft) and 6.1 m (20 ft) wide.

The LCC for this analysis was based on competitive bids from the Florida project, for which the AIT CT girder was selected. The research documents the economic impacts of the different materials and compares them over a 100-year service life, including estimated construction and maintenance costs. The prices for construction costs were estimated by Wozniak using estimates from their literature review for the bridges in similar coastal environments. A summary of the cost associated in the LCC for the three different bridge designs can be seen in Table 10.

It was estimated that the same deterioration trends will occur for the rebuilt prestressed concrete girder reinforced with carbon steel reinforcement. The deterioration trend assumed would require three bridge replacements during the 100-year analysis. The LCC also shows that the initial costs of construction of the CT girder bridge is between the cost of the carbon- and stainless-steel reinforced designs (Table 10).

Table 10: Summary of the life cycle cost results in US dollars ($) for three different bridge designs using different materials - fiber reinforced polymer (FRP) composite, carbon steel and stainless steel (adapted from Wozniak 2021).

Item	AIT Composite (FRP) Tub Girder	Prestressed Concrete Girder	
		Carbon Steel Reinforcement	Stainless Steel Reinforcement
Bid 1 ($)	268,062	220,359	448,019
Bid 2 ($)	279,176	140,513	285,260
Bid 3 ($)	585,000	288,000	585,000
Average Initial Construction Costs ($)	377,413	216,291	439,426
Number of Builds Required	1	3	1
Life Cycle Construction Costs ($)	377,413	648,872	439,426
Estimated Maintenance Costs ($)	238,550	377,717	277,746
Total Life Cycle Cost ($)	615,963	1,026,589	717,172

Results of the research indicate the cost of AIT's CT girder bridge is the most economical compared to either the carbon steel or stainless-steel models for the environmental conditions considered. In part, this is a result of the CT girder estimated to have the lowest maintenance costs over its service life. The CT girder is estimated to cost 40% less ($410,200 US dollars [USD]) than the carbon-steel reinforced-concrete bridge, and 14% less ($101,200 USD) than the stainless-steel reinforced-concrete design over 100 years (Table 10). A more detailed analysis and a breakdown of the methods is included by Wozniak (2021).

9.1.2. Design of an FRP Eco-bridge (wildlife overpass) in Sweden

Hällerstål & Sandahl (2018) investigated the feasibility of using FRP composites to construct wildlife crossings in Sweden. To model the use of FRP materials for a wildlife crossing superstructure, the Sandsjöbacka eco-bridge south of Gothenburg, Sweden, was redesigned using FRP. In addition to redesigning the wildlife overpass using both glass- and carbon-FRP materials, an LCC analysis was performed to compare the two composite designs to the original steel-reinforced concrete bridge.

The Sandsjöbacka eco-bridge was first contracted in 2015 and was completed in 2018. It cost an estimated $9.2 million USD to construct. The steel-reinforced concrete structure was cast onsite and resulted in a two-span bridge with a total length of 64 m (210 ft) and a width of 32 m (105 ft). During construction, a 600 m (2,000 ft) section of the highway had a reduced speed for a major portion of its three-year construction timeline and contributed to a social cost (user delay) in the LCC analysis. The eco-bridge was built with an expected 120-year service life.
Both FRP alternatives include a uni-mold girder system because it was believed to have the shortest construction time. These bridge sections are comparable to a long rectangular arched slab. Two different bridge systems were developed, one with glass-FRP (GFRP) and the other with carbon-FRP (CFRP) using design recommendations from The Prospect for New Guidance in the Design of FRP (Ascione et al., 2016). The depth of the GFRP girder was estimated to be 1.89 m (6.2 ft) and the CFRP girder was designed to a depth of 1.26 m (4.1 ft) for the 32 m (105 ft) required span. These two FRP bridge span designs were 81% and 91% lighter than their concrete equivalent, respectively.

The LCC analysis includes agency costs (e.g., materials, planning, operation, bridge disposal, etc.), initial construction, maintenance, and social costs (i.e., user delay) for the entire 120-year service life. Each bridge was assumed to have a service life of 120 years and therefore no additional construction costs were added for FRP structures. A summary of the estimated LCC costs are described in Table 11.

Table 11: Summary of the estimated life cycle cost (LCC) associated with different materials used for an overpass structural design in Sweden (Hällerstål & Sandahl, 2018).

Phase	Bridge Design Costs ($ USD)		
	Concrete	GFRP[1]	CFRP[2]
Planning	459,749	459,749	459,749
Construction	6,597,398	4,091,766	7,149,097
Maintenance	1,126,385	436,762	344,812
Disposal	17,356	10,459	9,540
Social	2,229,783	275,849	275,849
Total	10,430,670	5,274,585	8,239,046

[1] GFRP= glass fiber reinforced polymer
[2] CFRP = carbon fiber reinforced polymer

Analyzing the costs over the 120-year service life, the GFRP design costs an estimated 49% less ($5,156,085 USD) than the concrete equivalent, and the CFRP design costs 21% less ($2,197,024 USD) than the concrete bridge. This is largely influenced by the estimated costs for construction. The 510 days required to build the concrete eco-bridge increases construction costs dramatically compared to the 120 days estimated to build either of the FRP bridges. The high price of carbon is the main contributor to the higher costs of the CFRP compared to the GFRP bridge. The GRFP and CFRP bridges also have maintenance costs estimated to be 61% and 69% lower than the steel reinforced concrete bridge, respectively. Based on this research, a wildlife crossing made from GFRP was the most economic option over the 120-year service life of the structure. A more detailed analysis and cost breakdown is provided by Hällerstål & Sandahl (2018).

9.2. FRP LCC Analysis for US-97

To estimate the LCC of the FRP infrastructure along US-97 in Siskiyou County, different LCC assessment criteria were developed for the wildlife overpass and its associated wildlife crossing elements (e.g., exclusionary fencing, jump-outs). The analyses focused on the different materials, their associated construction costs, maintenance expenses, and estimated service life. To fully incorporate the expected long-term use of the wildlife infrastructure, a 100-year service life was used to conduct the LCC estimates. This analysis uses a discount rate (DR) of 2.5% to compare future costs to the present-day dollar value using the following equation:

$$Present\ Value = Future\ Value(1 + DR)^{-years}$$

9.2.1. Wildlife Overpass Girder Material

To conduct the LCC analysis for different girder types, a similar approach used for the fencing elements was used. The abutments and concrete deck were assumed to be the same for the superstructure regardless of the material used for the girders. To improve the durability of the concrete deck and abutments, FRP rebar and deck elements are recommended, but for simplicity, and to focus on the girder materials, the reinforcement and deck materials were all assumed to be the same.

Three girder types were considered: prestressed concrete bulb-tees, steel plate girders, and FRP composite tub (CT) girders manufactured by AIT (Figure 19). The cost of the concrete abutments for the wildlife overpass were assumed to be the same for the different girder materials and were not included in this LCC analysis.

9.2.1.1. Manufacturing and Construction Costs

The dimensions of the concrete and steel girders are based on the geometry used by AIT for the FRP CT girder. A girder spacing of 2.3 m (7.5 ft) was used to support an 18 cm (7 in.) thick normal weight concrete deck for all girders. The bridge span estimated for the US-97 crossing is 35 m (114 ft). A recommended bridge width of 50 m (164 ft) requires 22 girders for the wildlife overpass. A comparison of the different girder weights used in this analysis can be found in Table 12.

Table 12: Comparison of the estimated weights and construction costs for FRP, prestressed concrete bulb tee and steel I-girder.

Girder	Depth (in)	Unit Weight (lb/ft)	Total Weight (lbs)	Depth/Span Ratio
FRP Composite Tub	56	120	13,700	0.041
Prestressed Bulb Tee	54	686	78,200	0.039
Steel I-girder	54	280	32,000	0.039

The prestressed concrete girder considered is a California bulb-tee girder. A girder type with a 1.37 m (54 in) height was selected and has a depth-to-span ratio of .039. The depth/span ratio for the prestressed concrete bulb-tee is lower than the 0.045 recommended for simple-span prestressed concrete girder bridges but was considered acceptable for a wildlife crossing without vehicle traffic.

The Caltrans Comparative Bridge Costs guidelines (Caltrans, 2018) estimate that bulb-tee girders with spans from 27.4 to 44.2 m (90 to 145 ft) range from \$1,614 to \$4,037/m^2 (\$150-375/ft^2) for new bridge construction. Interpolating between the cost ranges for a 35 m (114 ft) span results in a unit cost of \$2,669/m^2 (\$248/ft^2). Multiplying the unit cost by the wildlife crossing footprint area of 1,736 m^2, (18,696 ft^2), a total construction cost of \$4,636,600 (2019 USD) was estimated for the bulb tee girder.

The steel I-girder selected for this analysis also had a height of 1.37 m (54 in) and a depth-to-span ratio of 0.039. The Caltrans Comparative Bridge Costs guidelines (Caltrans, 2018) estimate that steel I-girder bridges with 18.3-91.4 m (60-300 ft) spans range from \$3,498-7,535/m^2 (\$325-700/ft^2) for new bridge construction. Using the same wildlife footprint area and interpolating between these cost ranges, the estimated cost to build the wildlife crossing with steel girders is \$4,402/m^2 (\$409/ft^2) for a total of \$7,646,700 (2019 USD). Estimated costs for concrete bulb-tees and steel I-girders are shown in Table 13.

Table 13: Estimated costs for prestressed bulb tee and steel I-girders

	Estimated complete bridge construction cost	
Girder	per ft^2	Total
Prestressed Bulb Tee	\$248 /ft^2	\$4,636,600
Steel I-girder	\$409 /ft^2	\$7,646,700

Estimating the total cost to build a bridge using FRP CT girders is more challenging because the cost data is limited for FRP bridges and does not exist for FRP wildlife crossings. The cost to build the overpass was estimated by two methods and the average was used for the LCC analysis.

The first method used to estimate the construction of an FRP bridge for the US-97 site was to replace the estimated cost of the bulb tee and steel I-girders from the Caltrans total bridge cost estimates with the estimated costs of an FRP CT girder. The unit cost to furnish a precast bulb-tee for a 27-31 m (90-100 ft) span in California District 2 in 2017 according to Caltrans Contract

Cost Data (Caltrans, 2017b) was approximately $30,000 per beam. For 22 bulb tee girders, the unit cost per bridge area for the US-97 crossing was estimated to be $377/m² ($35/ft²).

Similarly, the approximate unit cost to furnish structural steel for a 2017 bridge widening project in District 2 was $2.00/lb using Caltrans Contract Cost Data (Caltrans, 2017a). This value was compared with a recent plate girder fabrication estimate of $2.55/lb from Pacific Steel in Billings, MT for 350,000 lbs of steel. Using an average cost of $2.25/lb, the unit cost per bridge area for 22 plate girders (700,000 lbs) was $904/m² ($84/ft²).

To obtain an estimate for the cost of a FRP CT girders, research results from (Brown et al., 2018) were used. The estimated cost for manufacturing an FRP CT girder was $5.25/lb of FRP infusion material (i.e., resin and fibers). Using the estimated weight (Table 12) from the preliminary CT girder geometry results in a cost of $71,900/girder for infusion materials. Increasing this value by 50% to account for labor, formwork, and fabrication results in a unit cost of $107,850. For 22 girders divided by the bridge area, the total FRP cost per bridge area is $1355/m² ($127/ft²). A breakdown of materials and labor for the FRP girders where not provided by Brown et al. (2018). A summary of individual concrete bulb tee, steel I- and FRP girders is shown in Table 14.

Table 14: Individual girder cost estimates

Girder	Estimated girder costs per girder	per ft²
Prestressed Bulb Tee	$30,000	$35/ft²
Steel I-girder	$71,500	$84/ft²
FRP CT girder	$107,850	$127/ft²

Subtracting the estimated unit costs of the prestressed bulb tee and steel I-girder (Table 14) from the estimated unit construction costs shown in Table 13 and averaging these values results in an estimated construction cost without girders of $2,895/m² ($269/ft²). Adding the estimated FRP tub girder unit cost to this value results in a girder estimate of $3,810/m² ($354/ft²). Using this estimate and multiplying by the US 97 bridge area results in a total cost of $6,618,400 (2019 USD). A comparison of the estimated construction costs can be seen in Table 15 with the calculated values used in this estimate and the total estimated cost for the three girder types.

Table 15: Comparison of FRP, prestressed concrete bulb tee and steel I-girder bridge construction cost estimates.

Girder	Complete bridge construction cost	Girder Cost/ft²	Estimated Construction Cost without Girders	Average Construction Cost without Girders	Total Estimated Cost
FRP Composite Tub	$354 /ft²	$127	-	-	$6,618,384
Prestressed Bulb Tee	$248 /ft²	$35	$213 /ft²	$269	$4,636,600
Steel I-girder	$409 /ft²	$84	$325 /ft²		$7,646,700

The bridge construction costs using CT girders is more expensive than a prestressed concrete bulb-tee and similar to the cost for steel girders. It is important to note that the lighter weight and potential accelerated construction methods available for FRP systems was not included and is likely to result in a conservative cost estimate.

9.2.1.2. Transportation Costs

The dimensions and weight of the different girders affects the associated transportation costs. It is expected that only one concrete or steel girder can be shipped on each semi tractor-trailer. Due to the geometry and light weight of the FRP material, four CT girders were assumed to be transported by each semi tractor-trailer. Due to the long load of the girder on each truck, the transportation convoys will require additional pilot vehicles. The cost per mile to transport each of these was estimated based on the quotes received from concrete, steel, and FRP manufacturers and were specific to their relative distance from the site on US-97.

For the LCC analysis, the average cost per mile of $6.43/km ($10.34/mi) was used for the three girders. The differences in costs were determined by the number of trucks required and the distance traveled. Currently AIT's CT girder is manufactured in Brewer, Maine, while steel and concrete girders are manufactured and shipped within California. Twenty-two semi tractor-trailers traveling 5,361 km (3,331 mi) from Brewer, Maine, to Weed, California, is estimated to cost $1.4 M and is not a realistic alternative for an FRP girder bridge on US-97. For projects where a large number of girders are required, AIT would pursue a local fabrication alternative where space would be rented and local labor used to create the formwork and CT girder fabrication. Many variables would influence a cost estimate for the local fabrication, however a very approximate estimate by AIT is $250,000. For the purpose of this LCC analysis, this on-site fabrication expense was substituted for a shipping cost for the FRP tub girders. For 22 semi tractor-trailers traveling shorter distances for the steel and prestressed concrete girders, it was estimated to cost approximately $43,450 to deliver the concrete girders from 307 km (191 mi) away, and $66,880 to deliver the steel girders from 473 km (294 mi) away.

9.2.1.3. Maintenance Costs

Maintenance costs associated with concrete and steel bridge structures is generally understood because of the large number of bridges built with these materials around the world. It is more challenging for FRP materials because some of the oldest FRP bridges in the world are just over 30 years old. It is expected that FRP materials have lower maintenance costs when compared to concrete and steel due to its durability and ability to resist corrosion. Research suggests that FRP bridges require up to 80% less maintenance associated costs over their expected service life compared to concrete and steel (Patljak, 2018).

For the LCC analysis completed in this study, maintenance estimates were based on predicted future costs and associated costs per area over the estimated service life of the structure. Based on historical bridge data (Barker, 2016) and FRP bridge LCC studies (Hällerstål & Sandahl, 2018; Wozniak, 2021) it was assumed that FRP CT girders will require $68,500 ($\$1.1/m^2$ [$\$0.1/ft^2$]) of maintenance over its service life. Prestressed concrete girders will require $136,900 ($\$2.2/m^2$ [$\$0.2/ft^2$]) and a steel girder bridge will cost $308,000 ($\$4.8/m^2$ [$\$0.45/ft^2$]). It is important to note that the prestressed concrete and steel girder estimates were based on highway traffic and it is likely the maintenance on these structures would be less for service loads created by animal crossings.

9.2.1.4. Service-life

It is difficult to identify the actual service life of an FRP girder bridge because they have only recently been used in bridge infrastructure. Furthermore, the true service life of wildlife crossing structures covered with natural landscapes rather than carrying vehicle traffic is not fully understood. It has been identified that concrete and steel bridge structures have an average service life between 70-80 years for vehicular bridges (Barker, 2016). A minimum service life of 75 years is recommended for all bridges designed by Caltrans. When it comes to wildlife overpasses, there is even less data available. It is expected that a wildlife crossing will not be subjected to vehicle traffic; therefore, concrete and steel girder bridges could likely reach a service life extending beyond 100 years. As a result of the uncertainty, and to minimize assumptions, a minimum service life is used for each of the structures: 75-years for concrete and steel, and 100-years for FRP. An additional \$161/m^2 (\$15/ft^2) was added to each 75-year service-life analysis for the cost of removing the original bridge structure.

9.2.1.5. LCC Results

A summary of the estimated LCC values for bridge girder material type can be seen in Table 16. The steel bridges are estimated to cost the most out of all three material options, costing \$9.28 million. The least expensive LCC is the concrete girder bridge at \$5.85 million. The FRP CT girder bridge is estimated to cost \$6.47 million.

Table 16: LCC estimates for the three girder material types.

Wildlife Overpass Procedure	FRP	Concrete	Steel
Service life (years)	100	75	75
Manufacturing and construction costs (\$)	6,150,984	5,664,678	8,890,676
Transportation costs (\$)	250,000	50,269	77,376
Maintenance costs (\$)	68,454	136,907	308,042
LCC Total (\$)	6,470,438	5,851,854	9,276,094
LCC \$/m^2 (\$/ft^2)	3,724 (346)	3,369 (313)	5,339 (496)

Note: all dollar values are presented in present value. Future costs have been converted to 2019 USD based on a 2.5% discount rate.

9.2.2. Wildlife Fencing Elements

An LCC analysis was performed on FRP, steel, and concrete materials used to construct wildlife fencing and associated elements. Caltrans' preliminary drawings for the wildlife crossing site on US-97 and were an estimate of the wildlife crossing's "footprint" or area that would be modified by both the overpass structure and its fencing. The wildlife fencing extends on both sides of the road and on both sides of the overpass to form the mitigated section of highway. As part of the crossing design, jump-outs (egress ramps that allow wildlife to exit the roadside of the fence) were included every 0.3-0.5 km (0.2-0.3 mi) and were based on recommendations from Huijser et al. (2015, 2016). It was assumed a cattle guard or gate would be located at each road access point along the US-97 mitigation area where it penetrates the wildlife fencing. A summary of the approximate values of the different elements included in the LCC is described in Table 17.

Table 17: Crossing elements and work zone values for US-97 LCC analysis.

Mitigation Elements	Value
Total Wildlife Fence Length, mi (km)	18.2 (29.3)
Fencing Length, North of Overpass, mi (km)	8.4 (13.5)
Fencing Length, South of Overpass, mi (km)	9.9 (15.9)
Work Zone Length, mi (km)	9.0 (15.5)
Total Number of Fence Posts	8021
Total Number of Jump-outs	95
Total Number of Road Access Points	24

Note: These element values do not represent actual values settled on for the US-97 mitigation site. These were approximations used by the WTI Team to investigate the LCC for different design element materials.

Itemized costs from two bids for a recent wildlife fencing project in Northern California along Highway 395 were used for developing the LCC. The itemized costs of the various fencing elements included in the bids are described in Table 18. The lengths and quantities shown in Table 17 and the costs in Table 18 were used to estimate the associated costs for constructing the different mitigation elements for the US-97 location and form the basis for the LCC analysis.

Table 18: Estimated costs to construct crossing elements based on a recent Caltrans fencing project.

Wildlife Infrastructure	Unit	Value		
		Bid 1	Bid 2	Average
Labor	Days/Mile	20	17	19
Initial Landscaping for New Fence	$/Mile	76,948	110,376	93,662
Agency Expenses for Construction	$/Mile	87,886	84,594	25,735
Wood Waste Disposal	$/mile	735	7,000	3,885
Remove Wildlife Fence	$/Mile	33,686	132,000	82,843
Remove Cattle Guard	$/Cattle Guard	1,032	7,500	4,266
Install Cattle Guard	$/Cattle Guard	22,745	10,000	16,373
Concrete for Jump-outs	$/Jump-out	88	570	329
Retaining Wall for Jump-outs	$/Jump-out	3,172	18,900	11,036
Steel Wire Mesh Gate	$/Gate	1,000	5,000	3,000
Stain Galvanized Surfaces	$/Mile	5,677	8,734	7,205
Install Post Fence	$/Mile	16,315	52,800	34,584

Two methods were used to estimate the cost of different materials required for the various mitigation elements. First, manufacturers of FRP lumber elements were contacted to see if actual estimates can be established based on the dimensions and number of units required. Only two companies where able to provide estimates for recycled plastic FRP fence posts and boards, Tangent Materials and Engineered Plastic Systems. The second method was to search for material prices online, which were combined with the estimates from Tangent Materials and Engineered Plastic Systems to obtain an average estimate for the price of one unit of each material such as one fence post. The individual cost of FRP boards were higher than large volumes of units from the two manufacturers. The summary statistics for the material cost estimates per element unit can be found Table 19 and include the material estimates for each fencing element. The mean of the material cost for each element is used in this LCC. All the cost estimates for the FRP materials are manufactured from recycled plastics, i.e., they are not made with virgin resins.

Table 19: Summary of the estimated average costs of crossing elements based on two contractor bids for a Caltrans fencing project and a review of online prices.

Material	Cost in US Dollars ($)/ Element Unit	Number of Element Units	Cost in US Dollars ($) Per Element			
			Min.	Max.	Mean	Std. Dev.
Wire Mesh Fencing	$/Mile	7	5,654	20,446	10,814	5,797
Steel Fence Post	$/Mile	7	13,163	37,348	24,494	9,413
Wood fence Post	$/Mile	4	3,910	30,812	14,443	11,545
FRP Fence Post	$/Mile	2	26,502	89,575	58,038	44,600
Metal Rail Element	$/Jump-out	5	234	934	525	284
Wood Board	$/Jump-out	12	239	559	340	87
FRP Board	$/Jump-out	12	1,331	4,504	3,067	1,219
Steel Access Point	$/access point	5	598	1,698	1164	445
Wood Access Point	$/access point	12	120	400	210	81
FRP Access Point	$/access point	12	784	3,217	1,998	818

9.2.2.1. LCC Results for Fencing Elements

The LCC analysis for the fencing elements included the costs associated with the purchase of raw materials and the costs associated to construct and rebuild the fencing at the end of its service life. Fence maintenance and social costs where disregarded because repair (e.g., broken wire mesh, vehicle strikes, etc.), materials, and labor for fence repair were assumed to be the same regardless of the material used. A service life of 35 years was assumed for the wood fence posts and steel posts were assumed to last 50 years. A service life of 100 years was used for the FRP materials based on available information from the manufacturers. Results of the LCC analysis are presented in Table 20.

Results of the 100-year LCC analysis for wood, steel, and FRP wildlife fencing elements suggest large differences between the estimated costs. The LCC for wood elements is the highest of all the materials and FRP elements is the lowest. It is estimated that steel and FRP elements are 14% ($781,065 USD) and 38% ($2,146,020 USD) less expensive than wood elements over the 100-year analysis, respectively. FRP materials are estimated to cost 28% ($1,364,955 USD) less than steel elements. The total cost includes all wildlife fencing elements (e.g., landscaping, fencing, jump-outs, access points, disposal, etc.). A summary of the ranked LCC estimates from least to most expensive can be seen in Table 21.

The estimated LCCs show the benefit of including the increased service life to realize the full potential of an FRP fencing elements. Initially, constructing crossing elements with wood material has the lowest estimated costs. However, when a 100-year service life is considered, FRP becomes the least expensive option at $118/m ($36/ft) (Table 21). In addition, because the FRP is manufactured with recycled plastic, it becomes a more sustainable alternative.

Table 20: LCC estimates for wildlife fencing elements for the three material types.

Wildlife Infrastructure	Wood			Steel			FRP		
	Cost per Unit ($)	# of Builds	100-yr Cost ($)	Cost per Unit ($)	# of Builds	100-yr Cost ($)	Cost per Unit ($)	# of Builds	100-yr Cost ($)
Grading and Landscaping	845,768	1	845,768	845,768	1	845,768	845,768	1	845,768
Agency Construction Costs	232,390	3	371,574	232,390	2	300,002	232,390	1	232,390
Install Wildlife Fence and Jump-outs	630,466	3	1,008,068	630,466	2	813,896	630,466	1	630,466
Post Fence Materials	460,432	3	736,196	643,664	2	830,933	1,255,177	1	1,255,177
Jump-out Materials	32,273	3	51,602	49,853	2	64,357	291,399	1	291,399
Install Cattle Guard	163,725	3	261,784	163,725	2	211,360	163,725	1	163,725
Install Access Gate	24,000	3	38,374	24,000	2	30,983	24,000	1	24,000
Access Point Materials	5,034	3	8,049	27,941	2	36,070	47,947	1	47,947
Remove Fence, Jump-outs, and Gates	1,510,232	2	2,146,599	1,510,232	1	1,510,232			
Remove Cattle Guard	42,660	3	68,210	42,660	1	42,660			
Wood Waste Disposal	70,824	2	100,667						
Stain Galvanized Surfaces				131,352	2	169,567			
LCC Total			5,636,891			4,855,826			3,490,871
LCC/mi			309,210			266,365			191,490
LCC/ft			59			50			36

Note: All dollar values are US Dollars and are presented in present value. Future costs have been converted to 2019 USD based on a 2.5% discount rate.

Table 21: Ranked LCC estimates for the three material types for both mitigation designs in US dollars ($).

Material Used	Wildlife Fencing 100-year LCC Estimates			
	Initial Construction ($)	Total ($)	$/Mile	$/ft
FRP	3,490,871	3,490,871	191,490	36
Steel	2,749,158	4,855,826	266,365	50
Wood	2,394,088	5,636,891	309,210	59

9.3. Summary of Findings

This report's LCCs focused on bridge girder types and fencing elements. There are additional applications of FRP materials (e.g., rebar, deck, abutment wrap) that may prove effective for cost and weight saving alternatives in future wildlife crossing designs and their LCC analyses. This analysis aimed to simplify the comparison and focused on specific material applications and assumptions (e.g., equal fence maintenance costs, identical bridge deck and abutments, etc.).

The total service life of FRP has not been documented due to the lack of real-world data. The LCC analyses in this report, along with the case studies, demonstrate that FRP can be a cost saving option for wildlife infrastructure over its service life. Furthermore, the environmental costs of using FRP compared to traditional materials could enhance the cost competitiveness if the use of recycled materials, end-of-life disposal, and other environmental advantages of FRP that could be incorporated into future, more detailed LCC analyses. Some of the key economic results of the LCC analyses are:

- The initial cost of FRP girder bridges may be higher than concrete and steel types, but their life cycle costs are lower due to their durability and the assumed reduction in maintenance costs.
- AIT's FRP composite tub bridge in Florida was estimated to cost 40% less than a prestressed concrete girder reinforced with carbon-steel and 14% less than the same prestressed concrete girder with stainless-steel reinforcement after 100 years in service.
- A glass fiber-reinforced polymer (GFRP) wildlife overpass was estimated to cost 49% less than its concrete equivalent, and 21% less than a carbon fiber-reinforced polymer (CFRP) design over a 120-year service life.
- A glass strand FRP wildlife overpass has maintenance costs estimated to be 50-80% less than steel and concrete equivalents.
- Using recycled plastic FRP for wildlife fencing, jump-outs, and road access points along US-97 is estimated to cost 38% less than wood and 28% less than steel over 100 years.
- The CT girder manufactured by AIT is estimated to cost 11% more than the prestressed concrete bridge and 30% less than the steel bridge over 100 years.

10. CONCLUSION

FRP materials are high strength, light weight, and extremely resistant to corrosion and environmental deterioration. These types of materials can support modular construction design and can be used to follow the principles of accelerated bridge construction. The size of FPR structures is not restricted by the technology itself but rather by transportation logistics and the ability to manufacture such large structures.

The ability for FRP materials to resist environmental degradation makes them a popular choice for marine environments and other harsh sites. The high strength-to-weight ratio of FRP composites make them very durable and require little to no maintenance for their entire service life. Reduced maintenance costs and their accelerated bridge construction capabilities make FRP materials competitive when compared to conventional construction products, such as concrete and steel.

The estimated life cycle cost (LCC) analyses in this report demonstrated that using FRP materials for a wildlife overpass and its associated fencing were found to be economically competitive with the use of traditional materials. The LCC analysis using FRP composite tub girders for the overpass structure design at the US-97 site was 11% more cost effective than a concrete girder bridge and 30% less cost effective than the equivalent structure made of steel. The use of recycled plastic FRP fencing elements cost 39 percent less over a 100-year service life than steel.

An evaluation of the wildlife crossing design in this report (e.g., overpass, fencing, jump outs, access points) shows that the use of FRP materials is cost competitive with more traditional wood, steel and concrete alternatives. Wildlife fencing using wood and an overpass made from concrete were estimated to cost $10,453,856, in 2019 US dollars (USD) over a service life of 100 years. A wildlife overpass using an FRP girder system for the structure and recycled plastic FRP for the fencing was estimated to cost $9,961,309 (2019 USD), 5% less than the crossing using concrete and wood. This LCC analysis suggests FRP materials can provide an economically viable option to traditional materials for a wildlife overpass if initial construction, long-term maintenance, and replacement costs are accounted for, and an LCC analysis is conducted using a 100-year service life.

This project’s preliminary design using FRP materials in a wildlife overpass, for a specific crossing location on US-97 in California, has provided a practical example of a feasible, cost efficient, and constructible wildlife crossing. The US-97 preliminary design benefits from the use of FRP materials in the superstructure, concrete reinforcement, fencing, and light/sound barriers. This project documents a potential FRP wildlife overpass design that can be implemented by a state DOT with minimal departure from traditional materials and construction techniques.

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12. APPENDIX A: FRP MANUFACTURER INFORMATION

Table 22: Contact information for leading manufacturers capable of creating materials necessary for an FRP wildlife crossing overpass.

FRP Companies Capable of Making Wildlife Crossing Infrastructure								
Company	**Location**	**Contact Name**	**Phone**	**Email**	**Website**	**Types of FRP structures**	**Specification Available**	**Figure Reference**
Pultrusion Companies								
Composicon	USA: Hayward, CA		510-538-8556	composicon@comcast.net	www.composicon.com	Pedestrian/trail bridges, barrier walls, platforms and walkways, structural fabrications, custom moldings.		
Bedford Reinforced Plastics	USA: Houston, TX, Salt Lake City, UT, Lafayette, LA		814-285-3979	online contact	https://bedfordreinforced.com	Trail bridges, grated walkways, and custom shapes		
Creative Pultrusions (Composite Advantage)	USA: Alum Bank, PA		888-274-7855	online contact	https://www.creativepultrusions.com/	Trail bridges, decking, wall panels, and structural beams	Material properties, installation, design	
Axion Structural Innovations	USA: Zanesville, OH		740-452-2500	info@axionsi.com	http://axionsi.com	RECYCLED PLASTIC: boardwalks, decking, support beams, pilings, and foundation mats	Material properties	
FiberGrate	USA: Dallas, TX		800-527-4043	info@fibergrate.com	www.fibergrate.com	Structural profiles, plates, grates, ladders, stairs, platforms, custom molds, and sound barriers (STC of 30 and class 1 fire retardant)	Installation, soundscape, some material properties	
American Plastic Lumber Inc.	USA: Shingle Springs, CA		877-677-7701	sales@aplinc.com	www.american-plasticlumber.com	RECYCLED PLASTIC lumber	Material properties	
Liberty Pultrusions	USA: Pittsburgh, PA		412-466-8611	sales@libertypultrusions.com	www.libertypultrusions.com	Structural profiles, threads/studs/nuts, rods, precision mechined parts, custom fabrications	Material properties	
Tangent	USA: Aurora, IL		630-264-1110	online contact	www.tangentusa.com	RECYCLED PLASTIC structural lumber, mats	Material properties	
Bedford Technology	USA: Worthington,MN		800-721-9037	online contact	https://plasticboards.com/	RECYCLED PLASTIC structural lumber, fence posts	Material properties	
Strongwell	USA: Bristol, VA		276-645-8000	online contact	www.strongwell.com	Panels, bridge decks and superstructures, retaining walls, nuts/bolts, structural shapes, sound barriers, grates, foam-core building panels	Material properties	
Kenway Composites	USA:		207-622-6229	info@kenway.com	www.kenway.com	Pultruded structural profiles		
Fiberline	Europe: Meddelfart, DK		45 70 13 7713	fiberline@fiberline.com	https://fiberline.com	Structural profiles, decking, pedestrian bridges, re-bar, and hybrid structures	Some material properties	
Vacuum Assisted Resin Transfer Companies								
Advanced Infrastructure Technologies	USA: Brewer, ME			online contact	www.aitbridges.com	Bridge in a Backpack (CFFT), hybrid composite beams	Maintenance, design	
Hillman Composite Beams	USA: Chicago, IL		847-722-4072	hillmanjr@hcbridge.com	www.hcbridge.com	Hybrid Composite Beams	Material properties of the FRP shell	
Guardian Bridge Rapid Construction	Canada: St. Marys, ON		519-831-9989	crawford@bridgedecks.ca	www.bridgedecks.ca	Decks, uni-mold bridges, and hybrid structures		
Orenco Composites	USA: Roseburg, OR	Eric Ball	541-580-2350	eball@orenco.com	www.orencocomposites.com	Uni-mold bridges with InfraCore technology		
Mostostal Warszawa	Europe: Warsaw, PL		48 22 250 7025	info@mostostal.waw.pl	www.mostostal.waw.pl	Decks, hybrid composite beams and girders		
FiberCore Europe	Europe: Rotterdam, NL		31 (0)10 476 5858	info@fibrcore-europe.com	https://www.fibercore-europe.com/en/	Uni-mold bridges, decks	Technical data sheet	
Lifespan Structures	Europe: Mitcham, UK		0203 146 7332	martin@lifespanstructures.com	https://lifespanstructures.com/	Uni-mold bridges, decks		
Delft Infra Composites BV	Europe: Delft, NL		03 46 25 9290	info@infracomposites.com	https://www.infracomposites.com/nl/	Uni-mold bridges		
Applied Advanced Technologies	Asia: Moscow, RU		7 495 261 30 33	online contact	http://www.apatech.ru/index_eng.html	Uni-mold bridges, pultrusion pedestrian bridges, decks		

Table 23: A summary of the technical data available for each FRP manufacturer available on their websites. Some of the manufacturers have additional data available, where some of them have none do to the complexity and design characteristics of creating vacuum molded FRP structures.

Company	Molding Process	Description	Notes on Material Properties	Modulus of Rupture, x	Modulus of Rupture, y	Modulus of Elasticity, E_x	Modulus of Elasticity, E_y	Shear Modulus	Ultimate Shear Stress	Ultimate Tensile Stress, x	Ultimate Tensile Stress, y	Ultimate Compressive Stress, x	Ultimate Compressive Stress, y	Secant Modulus @ 1% Strain	Stress @ 3% Strain Flexural Property	Water Absorption	Flame Spread Index
Advanced Infrastructure Technologies	Vacuum	Single and double radious arches for CFFT bridges up to 90 ft	No technical data														
American Plastic Lumber, Inc	Pultrusion	Structural HDPE Recycled Lumber	Stiffness and strengths can be increased by reinforcement and processing conditions			221,260 psi								137,861 psi	2,114 psi	< 0.1	
American Plastic Lumber, Inc	Pultrusion	Structural Reinforced HDPE Recycled Lumber		4,100 psi		400,000 psi										0.2	150
American Plastic Lumber, Inc	Pultrusion	Structural Reinforced Plastic Lumber		2,750 psi					800 psi	3,623 psi		2,842 psi	1,482 psi	306,080 psi		0.06	62
Applied Advanced Technologies	Both	Pultrusion and Uni-mold bridges	No technical data														
Axion Structural Innovations	Pultrusion	Recycled Stuxure Composite Boards		3,000 psi		220,000 psi			350 psi	3,600 psi		3,000 psi	1,200 psi			0.04	147.4
Bedford Reinforced Plastics	Pultrusion			30,000 psi	10,000 psi	2,800,000 psi				30,000 psi	7,000 psi	30,000 psi	15,000 psi				
Bedford Technologies	Pultrusion	BarForce Recycled Plastic Lumber with Fiberglass bars	Stiffness and strengths can be increased by reinforcement and processing conditions	3,900 psi	4,900 psi					3,623 psi	3,623 psi					0.06	62
Composicon			No technical data														
Creative Pultrusions	Pultrusion	Pultex SuperStructural Profiles	Stiffness and strengths change based of the thickness and shape of the cross section	43,500 psi	24,000 psi	2,800,000 psi		500,000 psi		31,000 psi	16,500 psi	38,800 psi	25,500 psi			0.6	
Delft Infra Composites BV			No technical data														
FiberCore Europe			No technical data														
FiberGrate	Pultrusion	Sound Barrier		30,000 psi						30,000 psi		30,000 psi					25
Fiberline			No technical data														
Gaurdian Bridge Rapid Construction			No technical data														
Hillman Composite Beams	Vacuum	Hybrid composite beams up to 120 ft	FRP Shell only			3,100,000 psi	2,300,000 psi	1,010,000 psi	19,100 psi	27,800 psi	20,600 psi	27,800 psi	20,600 psi				
Kenway Composites			No technical data														
Liberty Pultrusions	Pultrusion	Structural Profiles		30,000 psi	10,000 psi	2,500,000 psi			4,500 psi	30,000 psi	6,500 psi	30,000 psi	15,000 psi			0.6	25
Lifespan Structures			No technical data														
Mostostal Warszawa			No technical data														
Orenco Composites			No technical data														
Strongwell	Pultrusion	Structural Shapes	Stiffness and strengths change based of the thickness and shape of the cross section	30,000 psi	10,000 psi	2,600,000 psi		425,000 psi		30,000 psi	7,000 psi	30,000 psi	15,000 psi			0.6	

13. APPENDIX B: PROPOSED DESIGN LOCATIONS

13.1. Submitted Design Sites

This appendix sections includes a summary of the five proposed design locations for an FRP wildlife overpass that where not selected for this project. Each location has been summarized based on the proposals submitted to the WTI Team. It includes all the important information that was provided about each site and is what was sent to the TAC members for their feedback on which location is most suited for this design project.

13.1.1.1. USA Parkway/State Road 439 in Storey County, Nevada

This proposed site is located just south of the city of Clark, Nevada, which is about 15 miles east of Reno (Figure 44). It is a four-lane highway with a center left-turning lane, i.e. five lanes in total. This area gets lots of exposure due to its location and the amount of traffic using the state highway.

Figure 44: Proposed design site location for SR-439 in Storey County, Nevada.

The proposed site for a wildlife overpass is located on a blind s-curve. This location has been identified as one of the top safety hotspots in Nevada related to AVCs and is the area with the most frequent feral horse-vehicle collisions per year. This location has support for a wildlife overpass to address safety concerns by horse advocate groups. The main blockchain property owners are supportive of horses and is currently organizing a working group to manage horse movements in the area and have support from most of the businesses in the area.

The four-lane road with center median presents a larger challenge given the span the bridge will require. There is currently no FRP bridge designed and tested that is capable of such a large span. Although we are confident this material can achieve such a distance, it is beyond the scope of this project and result in additional challenges in design and implementation. Therefore, the FRP bridge will have to be designed to land in the center median. Fencing for horses is different than wildlife and will need to be upgraded to not allow wildlife to penetrate it. A concern is that there is lots of businesses in the area and therefore lots of access points that will have to be dealt with regarding fencing. The fence will either have to have a lot of breaks in the fence or be fenced around the perimeter of the whole business complex.

13.1.1.2. State Road 139 in Modoc County, California

This proposed site is located between post miles 30 and 40 on SR-139 in northern California (Figure 45). It is a two-lane road with 12 ft lanes and 4 ft shoulders on each side. The surrounding adjacent land is generally flat with little change in elevation.

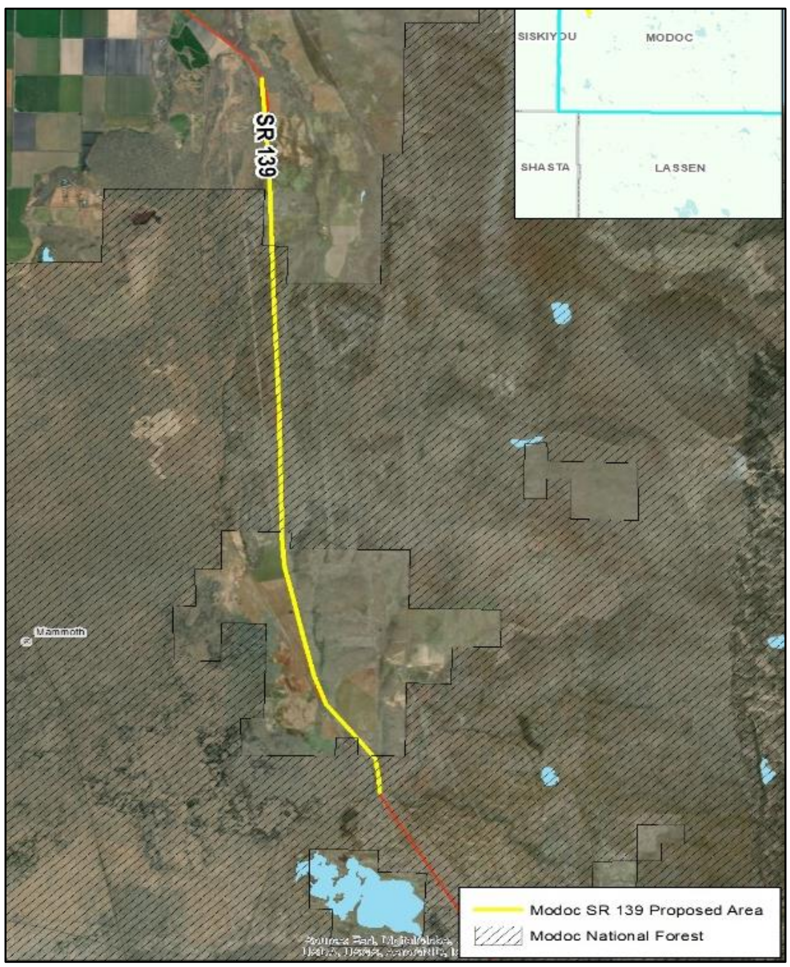

Figure 45: Proposed site location for SR-139 in Modoc County, California.

The target species for the wildlife overpass is mule deer. This section of road passes through the Interstate Herd winter migration route (Figure 46). Deer commonly congregate near, and on, the road during winters with above average snowfall. There have been over 100 dead deer counted along the road during winter migration.

Figure 46: Mule deer crossing SR-139 during the winter months.

This area has the support of local and state agencies. The CDFW, California Highway Patrol (CHP), California Deer Association (CDA), and the Modoc public have identified this as a problem are and are concerned about safety. Caltrans plans to mitigate this the area with a crossing structure and wildlife fencing in the future.

This is a low volume road but has extra-large, slow-moving, agricultural vehicles. This can create problems when addressing the clearance envelope required for the overpass, as the normal clearance allowance will most likely be insufficient to allow agricultural equipment to pass under it. It will have to be discussed further to figure out height requirements for the bridge and other challenges that may arise due to the size of agricultural equipment.

13.1.1.3. State Road 20 in Colusa County, California

This proposed site is located along SR-20 between post miles 9.8 and 12.4. It has been identified to have both safety and genetic barrier concerns by Caltrans and the CDFW. This location is due to receive a road realignment of the curves, wider shoulders, and rumble strips along certain areas of the road. Caltrans wants WVC mitigating infrastructure added to the construction plan. This would be ideal because there is not expected to be a large amount of future AADT growth and is not expected to receive any additional future lane expansions. The current peak traffic volume is about 870 vehicles/hour. This location has good exposure as this route is a major connector between California's central valley and the wine country to costal destinations within Mendocino, Sonoma Lake, and Humboldt County. There is a wide range of topography changes along this section of road that range from steep slopes and valleys to gentle grasslands and meadows. The CDFW has already obtained numerous conservation easements within the project area and are in the process of obtaining more.

The focal species for this area is elk. This has been prioritized by CDFW as an area of great concern for migratory and resident elk populations. Collaring data shows that SR-20 has become a barrier for the resident elk herd (Figure 47). Other wildlife in the area that will benefit from a wildlife overpass are deer, bear, cougar, coyote (*Canis latrans*), and other small animals. There is great existing inter-agency partnerships and relationships in both the environmental and engineering divisions that are in support of WVC mitigating infrastructure.

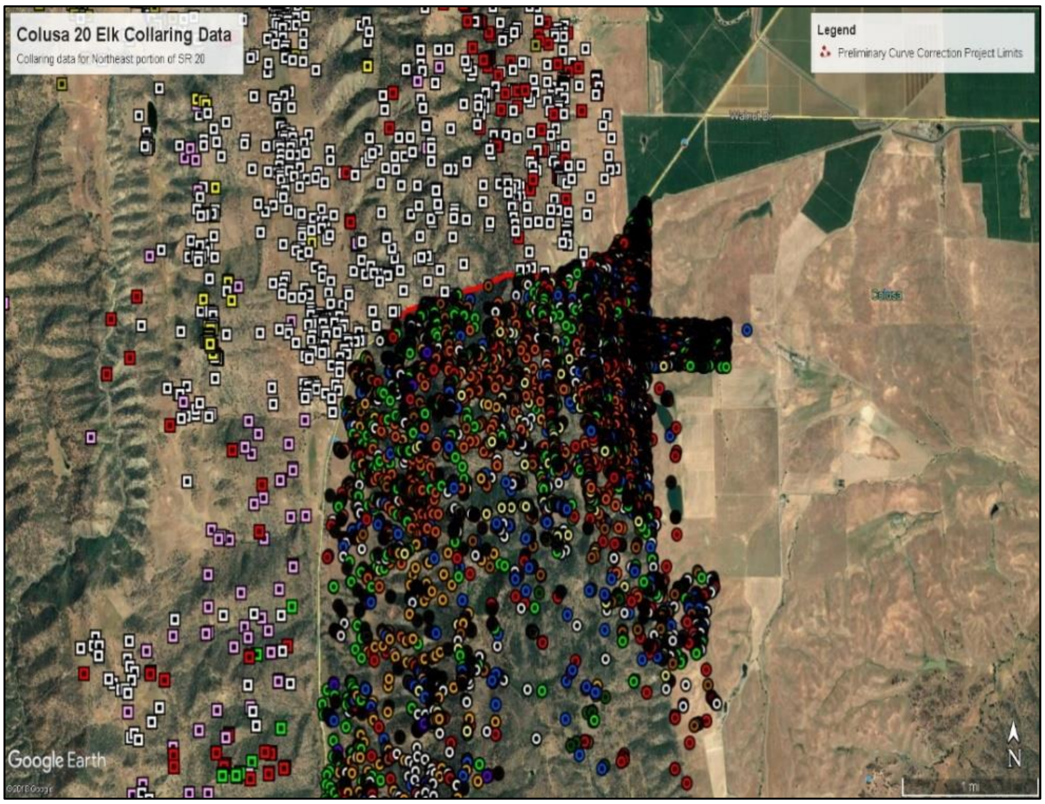

Figure 47: GPS data of collared elk along the proposed SR-20 mitigation site.

This site has various topography elements and gives options to placement and structure type. The barrier and safety concerns caused by the two-lane road make it an ideal site for a wildlife overpass and fencing.

13.1.1.4. U.S. Highway 101 in Humboldt County, California

This proposed site is located on a two-lane section of road along US-101 between post miles 113 and 116 (Figure 48). The current estimated AADT is 4,000 vehicles. The mitigation area is located within Humboldt Lagoons State Park (HLSP) and extends three miles south of the "Southern Gateway" to Redwood National and State Park (RNSP) system.

Figure 48: Proposed mitigation location along US-101 in Humboldt County, California.

This location has been identified as a high priority area for addressing wildlife connectivity. There are approximately 45,000 visitors to HLSP and up to 500,000 visitors to RNSP each year, with most of them traveling through the proposed site location. The surrounding area is generally flat and consists of slopes between 0-2%. Although the water table is only 30-39 inches below the surface, there is no ponding in the area and flooding is rare. There are no wetlands or bodies of water within 600 ft of the proposed location.

The target species for this area are Roosevelt elk, black-tailed deer, and black bear. They are also the most common mortalities along this section of road. GPS collared elk in the area were estimated to make 280-284 road crossings a year from 2017 to 2019. That is more than any other location monitored. This section of US-101 has one of the highest rates of deer-vehicle collisions across the entire state of California and is estimated to cost drivers an estimated $22,000 per mile per year. Other species an overpass will benefit are the endangered Humboldt marten (*Martes caurina humboldtensis*), the federally proposed threatened west coast fisher (*Pekania pennanti*), bobcat (*Lynx rufus*), beaver (*Castor canadensis*), river otter (*Lontra canadensis*), and coyote.

There is stated support by Caltrans District 1 management, environmental planning, design, and traffic safety departments for this mitigation site. There is also a local scientific community, including biologists and researchers from USFWS, CDFW, California State and National Parks, and Humboldt State University that are in favor of wildlife mitigation efforts to increase safety along this section of road.

Looking to connect threatened and endangered fishers and marten will involve landscaping that may require larger loads which can include trees and other large debris. Research on the crossings of these animals will help understand the structural loads required by the bridge superstructure. The site's close proximity to a campground and schoolhouse have add concerns about people climbing the fence and using the bridge, which will reduce the effectiveness of the mitigation measures due to human presence.

13.1.1.5. State Road 126 in Ventura County, California

This proposed site is located along a four-lane road with a center left-turning lane that follows the Santa Clara River. The study area is along SR-126 between post mile VEN-21 and LA-5. This section of road separates the Santa Susana Mountains from the Los Padres National Forest. The Fish Hatchery road location is the optimal site location for an overpass based on the land use restrictions within the area (Figure 49). There is protected quality habitat on both sides of the road with no steep cliffs and provides natural drainage. SR-126 is an important connector between US-101 in Ventura and I-5 in Santa Clarita. It is estimated to have an AADT of 26,000 vehicles and will have high exposure to the public.

Figure 49: Proposed mitigation location along SR-126 in Ventura County, California.

The focal species for this location are mule deer, cougar, and mule deer. Other animals that will benefit from wildlife mitigation infrastructure include coyotes, bobcats, and gray foxes. Caltrans is in support of this project.

The 4-lane road with center median presents a larger challenge given the span the bridge will require. There is currently no FRP bridge that is designed and tested that is capable of spanning such large distances. Although we are confident this material can achieve such a distance, it is beyond the scope of this project and result in additional challenges in design and implementation. Therefore, the FRP bridge will be designed to land in the center median. Due to high urbanization in the area, additional considerations to wildlife fencing is needed to funnel animals safely over the road and to protected areas.

14. APPENDIX C: ADDITIONAL PHOTOS FOR THE US-97 MITIGATION SITE

Figure 50: Grass Lake A potential site looking west.

Figure 51: The area north of Grass Lake A potential site that will require backfill to create the approach ramps for the wildlife overpass.

Figure 52: Standing south of US-97 on Grass Lake B looking west towards Grass Lake A.

Figure 53: Standing south of US-97 on Grass Lake B looking east-northeast towards the blind curve.

Figure 54: Grass Lake B looking south towards US-97 showing the little fill required for the approach ramps.

Figure 55: The railroad tracks south of US-97 at Grass Lake B proposed site.

Figure 56: Standing south of US-97 on top of the embankment at the proposed Horsethief Creek site, looking east-northeast.

Figure 57: Horsethief Creek site showing the change in elevation topography south of US-97.

Figure 58: North of US-97 at Horsethief Creek proposed site looking east-southeast.

Figure 59: Looking south over US-97 at Horsethief Creek proposed mitigation site.

Figure 60: The downhill, below grade, elevation change at the Horsethief Creek site looking east.

Figure 61: Mud Lake A proposed site looking west-southwest along US-97.

Figure 62: Mud Lake A looking northwest over US-97.

Figure 63: Habitat at Mud Lake A looking south-southwest.

Figure 64: Standing on the embankment west of US-97 at the Mud Lake B site looking north.

Figure 65: Overlooking US-97 at the Mud Lake B proposed site looking east.

Figure 66: Below grade road alignment at Mud Lake B looking south-southwest.

Figure 67: Below grade road alignment at Mud Lake B looking north-northwest.

Figure 68: Grass Lake Summit proposed site looking south towards Mt. Shasta.

Figure 69: Standing on embankment at Grass Lake Summit site looking east over US-97.

Figure 70: Grass Lake Summit site looking north-northeast along US-97.

Figure 71: Highest elevation point at Grass Lake Summit site looking south-southwest along US-97.

Figure 72: Standing on eastern embankment at the Grass Lake Summit site looking north over US-97.

15. APPENDIX D: SUMMARY OF PRELIMINARY VIRTUAL DESIGN LAB RESULTS

This appendix includes preliminary results from the virtual design lab (VDL) that focused on the application of FRP materials to a wildlife overpass and associated design elements.

15.1. FRP Wildlife Infrastructure Elements

Opportunities for the integration of a variety of FRP materials into the structural design of a wildlife overpass structure and its related wildlife crossing design elements have been organized based on discussions among experts and Caltrans personnel in the VDL.

15.1.1.1. Substructure: Footings

The use of FRP CT girders for the superstructure will be lighter than normal steel plate girders or prestressed concrete girders which may permit reduced load calculations for footings and other foundation design elements.

- *Enhanced*: For reinforced concrete will be used for footing or drilled piles, then the use of FRP reinforcement can be explored in place of black iron, stainless-steel, or epoxy-coated rebar.
- *Innovative*: If skin friction is not an issue in the geologic properties at the crossing location, then the use of FRP tubes may be considered for drilled piles' casing.

15.1.1.2. Substructure: Abutments

There are numerous abutments and wingwall designs available. They include, but are not limited to, poured concrete, mechanically stabilized earth (MSE), and bin wall designs. The abutment type influences what applications of FRP materials is possible.

- *Basic*: Abutments can be wrapped in FRP to protect the surface from environmental factors and increase the service life of the structure.
- *Basic*: Recycled plastic FRP material can be used in non-structural applications in place of large boulders or stones.
- *Enhanced:* For poured concrete abutments, the use of FRP reinforcing in place of black iron, stainless-steel, or epoxy-coated rebar can be considered.
- *Enhanced*: For MSE walls, there may be some possibilities to consider and explore the use of FRP strapping or FRP geotextile style mat.
- *Innovative*: The use of FRP abutment casings can be installed quickly prior to filling them with concrete. This casing can provide shorter construction times and increased service life compared to traditional wrapping methods, because the concrete will be protected from environmental elements on all sides.
- *Innovative*: FRP panels, or systems, may be able to be used for bin wall designs.

15.1.1.3. Superstructure: CT Girders

The WTI Team has conducted a scan of North American FRP manufacturers to assess their suitability to a wildlife crossing project. AIT's CT girder system is one of the few manufacturers capable of building a wildlife crossing of this scale. The girders in this section focus on the use of a FRP tub girder, and do not evaluate all the manufactures capable of building the 115 ft bridge span.

- *Basic*: The CT girder system is a closed-top hollow FRP tub girder that is simply supported on standard foundations with a pre-cast, or cast-in-place concrete deck.
- *Enhanced*: Filling the negative space within the tub girders is one enhancement that could be applied to an existing CT girder system. Tub girders filled with foam, or other lightweight materials, could provide sound attenuation from traffic underneath without dramatically increasing the weight of the girders.
- *Innovative*: Sections on the top of the CT girder can be left open to create planting pockets. These openings would provide more space for vegetation with deeper root development without increasing the depth of the soil across the entire structure. Additional research is required to assess the structural impacts from the openings in the concrete deck, as well as the evaluating the effects of moisture and rooting stress to the structural properties of the CT girder.

15.1.1.4. Superstructure: Deck

A precast concrete deck is the standard design used for the CT girders. It adds compressive strength to the structure and provides additional sound attenuation. Alternate materials have been identified to offset the ecological impact of concrete including the use of recycled materials such as crushed glass, fly ash, or ferrous concrete, and lightweight concretes have been developed and used in bridge decks.

- *Basic*: FRP reinforcement can be used in place of black iron, stainless-steel, or epoxy-coated rebar.
- *Innovative*: Recycled FRP aggregates (e.g., crushed wind turbine blades) could be integrated into the concrete mix to reduce the weight and increase the sustainability of the deck.
- *Innovative*: Use thin FRP panels as the subframe forms to connect CT girders. Concrete can be poured directly onto these panels, reducing the overall weight of the bridge span and accelerate bridge construction.
- *Innovative*: Incorporate bubble deck technology with FRP or recycled plastic spheres. A bubble deck incorporates air-filled balls into the reinforced concrete deck to reduce the decks weight.
- *Innovative*: A deck composed entirely of FRP. An FRP decks can be installed before or after the girders are put into place to reduce weight of the bridge span and decrease construction time.

15.1.1.5. Superstructure: Aesthetics

A huge benefit to using FRP materials for making a wildlife crossing structure more aesthetically pleasing, is the highly versatile and customizable properties of the composites. Designers can mold, carve, build, infuse, form, or 3-D print anything imaginable that can be connected to the side of the superstructure. This means that detailed aesthetic architecture can be constructed simultaneously during bridge construction and installed quickly.

- Basic: Any FRP aesthetic architecture that is installed to the side of the bridge superstructure without decreasing bridge strength or safety properties. False sides in the form of a facade or appliques, of wildlife or other images, could be cast in FRP and attached to the structure’s sides for architectural interest. The color customization of FRP could also be leveraged to blend into the surrounding landscape or to draw attention to the structure.

- *Basic*: The CT girders can have pigment added to them during manufacturing.
- *Enhanced:* FRP impact absorbers can be designed and installed to the side of the outer CT girders to reduce damage from an underside strike from vehicular traffic.
- *Enhanced*: Side members could be added to act as a false front to create the illusion of a more elegant structure such as an arch.

15.1.1.6. Corridor: Fencing and Jump-outs

Wildlife crossings need to be built with exclusionary fencing to guide the animals to the overpass and keep them off the road. FRP composites can be a direct replacement to traditional materials, including wood, steel, and concrete.

- *Basic:* Conventional exclusionary fencing is constructed using wood and/or steel elements. Wood fencing typically has a life cycle of 20-30 years.
- *Enhanced*: The use of FRP posts to replace wood or steel in wire mesh wildlife fencing. They are installed the same way as traditional materials and could result in a longer life span and with lower maintenance requirements.
- *Enhanced*: Pultruded FRP boards can be used to replace wood in traditional wildlife jump-out designs.
- *Innovative*: Replace wire mesh with an FRP mesh design.

15.1.1.7. Corridor: Sound and Light Barriers

These barriers vary from fence designs because they are built to block sound and light from penetrating the animal's field of view. Side treatments on the crossing structure assumes that some form of sound and light attenuation is required to shield the surface of the overpass from traffic

- *Basic*: Barriers are commonly made from concrete, wire mesh fence, soil berms, and other traditional applications.
- *Enhanced:* FRP façade/panels on side of structure could be incorporated into the architectural design of the structure negating need for additional aesthetic panels, fences, etc.
- *Enhanced*: Barriers can be constructed with pultruded boards or foam core structures.
- *Enhanced*: To replace wire mesh fencing, FRP grates and/or fence posts can replace traditional steel elements.

15.2. Environmental Landscaping

The top surface of the bridge is important in guide animals' use of the wildlife overpass. The type of landscaping is influenced by the target species and guided by the overall project goals. In general, WVC safety concerns are addressed with exclusionary fencing. The primary purpose of the crossing structure is to provide connectivity for the focal species. The crossing structure also offers an opportunity to create an environment conducive to the movement of other local species. The integration of elements beyond those required for conveyance of species of safety concern contributes to the overall ecological function of the structure to integrate into the surrounding environment. It is generally recommended that the landscape surface on a crossing structure reflects the surrounding environment in terms of habitat conditions and species composition.

The primary concern at the US-97 site is motorist safety, however strategic planting and design on the landscape surface can facilitate the movement of local species beyond those that pose a safety concern. For example, small species take longer to move across a structure and thus require additional habitat elements (e.g., hiding cover, water, food) to encourage use of structure. The effects of replacing the natural materials commonly used with artificial FRP elements is unknown. They should be used on an experimental basis and monitored alongside natural materials to assess animal use and integration into the environment. Because of these factors, most of the environmental design lab focused on the planting strategy, back-fill, and draining strategies, which are reflected in the WTI Team's structural design in the next chapter.

15.2.1.1. Environmental Parameters

There are countless ways to design the environmental landscape of the crossing structure. The US-97 mitigation site was used to guide the design lab's efforts of meeting the goals of the mitigation site, while adapting FRP composites into landscaping elements.

- *Safety*: The primary species of safety concern at the project site are black tailed deer and elk.
- *Connectivity*: Smaller wildlife species spend more time on a crossing structure, thus additional resources and basic life requisites are needed to support their movement
- *Drainage*: Water does not need to be retained on top of the structure and should be properly drained.

15.2.1.2. Surface and Approach: Substrate & Fill

The type of materials used for the substrate of the wildlife crossing determines they types of vegetation that can be planted on the structure. The species selected for landscaping are affected by both the depth and type of soil. The following options have been identified as suitable options for the surface: gravel; scree-type gravel mix, volcanic rock, engineered soils, and soilless mix (e.g., vermiculite and perlite). No plastics will be used in the soil mix.

- *Basic*: Back-fill is 100% natural materials
- *Enhanced*: Geofoams can be used in place of back-fill on the approach
- *Enhanced*: Large blocks made from recycled plastic can be used to replace back-fill on the approach.

15.2.1.3. Surface and Approach: Landscape Materials

It is preferred to use local species that are harvested in the area rather than the integration of cultivars, due to adjacent Forest Service lands. The use of native species is recommended with a focus on those present in the surrounding landscape to maximize the chances of success. Local live plants should be retained during overpass construction to the extent possible to replant on overpass.

- *Basic*: Only natural materials are used.
- *Enhanced*: Build planters using FRP boards.
- *Enhanced*: FRP can be molded to replicate rocks and other hiding material.
- *Innovative*: Create FRP trees for hiding cover and to mimic trees for smaller animal movements.

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