NCHRP 25-25, Task 93
LONG-TERM CONSTRUCTION AND MAINTENANCE COST COMPARISON FOR ROAD STREAM CROSSINGS: TRADITIONAL HYDRAULIC DESIGN VS. AQUATIC ORGANISM PASSAGE DESIGN

Prepared for:

AASHTO Standing Committee on Environment

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SPECIAL NOTE: This report **IS NOT** an official publication of the National Cooperative Highway Research Program, Transportation Research Board, National Research Council, or The National Academies.

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1.0 Introduction

The design and installation of road stream crossings to accommodate fish and aquatic organism passage is increasingly becoming a priority for state and federal regulatory agencies throughout the United States to meet the mandates of the Clean Water Act, and in the case with federally protected migratory species, the Endangered Species Act. While progress has been made in providing fish passage at dams on many river systems, these agencies realize that road crossings are much more numerous than dams and may have a greater impact on fish passage than dams as supported by inventories of road crossings conducted to assess aquatic passage in the Pacific Northwest. In addition, extreme weather events and other climate change concerns are driving discussions toward a new paradigm for infrastructure investment decisions that considers the overall life-cycle costs of structures. The higher costs of installing effective aquatic organism passage structures are often a concern for designers and transportation agencies. While it is clear that the upfront costs of larger structures may increase with effective aquatic organism passage designs, long term savings may be achieved by reducing the risk of road failure, reducing the need for periodic maintenance, increasing the life span of the structure, and reducing the cost of mitigation for open water and wetland impacts.

There are three general approaches to the drainage design of culverts that are in use across the nation, though variations in application occur. The three approaches include:

- Traditional or conventional hydraulic design: Culvert or bridge designed with only hydraulic and practical structural criteria taken into account
- Aquatic organism passage (AOP) design (HEC-26 and Bankfull width times a safety factor): Culvert or bridge designed with hydraulic, sediment transport, and habitat criteria taken into account to facilitate passage of fish and other aquatic species. This approach typically leads to a smaller crossing width than under stream simulation.
- Stream simulation design (geomorphic design): Culvert or bridge designed with hydraulic, sediment transport and stream geomorphology criteria taken into account to mimic functions of a natural stream and floodplain to maximize stream continuity.

Multiple states and federal entities have developed guidance regarding stream crossing design approaches, but the guidance focuses primarily on design approaches mentioned above and design options. While design options have been studied, research is needed to evaluate the long-term costs and benefits of aquatic organism passage design which can support decision making on project design and funding. The objectives of the overall Task 93 project research are to:

- Quantify the long-term costs of road stream crossings that span the bankfull width of a waterway (aquatic organism passage design) in order to provide an accurate picture of the total life-cycle cost of the structure.
- Compare costs of aquatic organism passage design-based structures to the costs of traditional hydraulic design structures.

2.0. Survey Methodology and Literature Review

2.1 Literature Review

Information on AOP design and costs was gathered through literature searches and review of other publicly available information. The literature review focused on sources of information that address design and construction practices and project effectiveness (post-construction monitoring, maintenance and resiliency performance). The initial literature review was also supplemented with additional contributions provided by panel members and survey participants. A summary of the literature and the implications from information and issues are included in Appendix A.

2.2 Surveys

Based on input from NCHRP, the research panel and Team resources, a list was assembled of over 50 individuals from resource agencies, DOTs, universities and nonprofits with knowledge of culvert and bridge design using traditional hydraulic design and aquatic organism passage design procedures, and with potential access to individual project design and cost data. The initial list of individuals included a range of states and agencies to provide thorough regional coverage so that regional and geographic variation in the state of practice could be represented.

The Team contacted each potential source and requested interviews. A series of nine interview questions were prepared and shared with each participant prior to the interview. In addition, an example project summary table was shared with each participant to assist in defining the type of project information sought. For each survey participant, brief phone interviews were conducted to follow up on responses, and to inquire about additional information sources or contacts. Information provided by the participants was used to develop the project summary table and to identify key issues in the state of the practice that may affect project costs.

Follow up interviews were conducted by email and phone with six DOTs, one non-profit organization and one state resource agency with the goal of obtaining additional information related to project costs, maintenance costs, and long term cost considerations associated with the project information provided during the initial surveys. Each entity had provided initial project information and indicated their interest in participating in a follow up interview. The initial list of questions reviewed during the detailed surveys is provided below:

- How many AOP retrofit projects have been performed in the past 10 years?
- What type of cost data is available for stream crossing designs and construction?
- How is risk reduction and reduced maintenance cost factored into design decisions?
- What are the educational, institutional, legal, technical, and economic barriers to AOP based designs versus traditional design approach?
- Can you provide a source to discuss routine culvert maintenance costs? Some DOTs use a ledger to track costs of individual maintenance actions which require pre-authorization. Access to this data, or an average annual cost, would be helpful.

- Are additional cost items available for each project identified and/or provided during the initial interview?
- In addition, the project summary table was shared with each participant to assist in gathering additional project information.

Project data was summarized by crossing type and structure as well as cost. The project data is most representative of northern latitude states where AOP design projects have a history of design and installation that has been spurred on by consent orders under the Endangered Species Act (ESA) for salmonids (i.e., Washington and Maine). The project costs were categorized by culvert structure type (bridge, pipe or box culvert) and by material (wood, metal or concrete) or form (3-sided or 4-sided box; arch or pipe). In general, metal structures are cheaper to purchase and install than a comparably sized concrete structure which typically requires concrete support appurtenances (footers and wingwalls), though variations occur based on design. Other cost items within the total cost value include design and permitting, ROW acquisition, and construction costs.

Each crossing structure was initially classified based on the type of structure as described in the project material received from the participants. This information was cross-checked with any supporting documentation received such as plan sets, bid tables, and reports and any discrepancy was resolved with the source of the information. Since AOP structure cost was the primary concern and the cost of the structure varied based on structure material and construction requirements for footers and other attendant features, each project was further organized based on structure type (bridge, pipe or box) and material construction (concrete, metal or wood).

3.0 Interview Results and Key Issue

3.1 Initial Survey Response

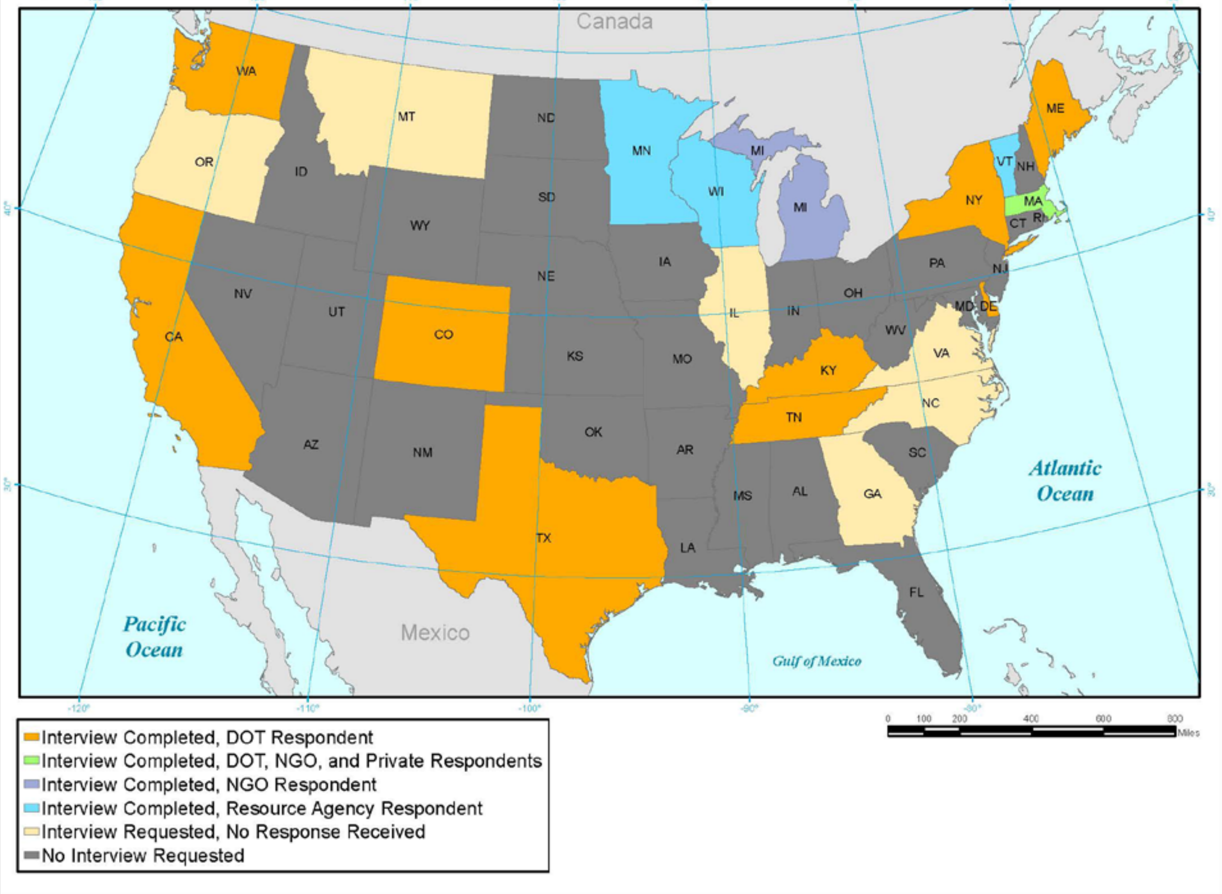
A total of 57 practioners from State Departments of Transportation and federal and state resource agencies, and university and nonprofit organizations were contacted to participate in the initial survey. A total of 19 practitioners responded to the request to participate in the survey (Figure 1). Among the respondents, 9 DOTs, 1 local government, 5 federal or state agencies, and 4 NGOs participated in the interviews. Additional contacts identified by the initial survey participants as sources for additional data were also contacted as part of follow up interviews.

Prior to the scheduled interview, participants were first provided with a list questions and a summary table listing the types of project cost data being sought. During the interview participants frequently discussed additional aspects of AOP culvert replacement projects that are relevant as either background information or for project design or cost considerations. This information is included in the key topic discussions presented in the following sections.

3.1.1 Regulatory Compliance

As part of the interviews, practitioners were asked what the drivers were for incorporating aquatic organism passage standards into stream crossing designs. One of the significant and perhaps earliest drivers is compliance with the Endangered Species Act (ESA) for federally listed fish species, particularly Atlantic salmon in Maine, and chinook, coho, chum and sockeye salmon in California, Idaho, Oregon, and Washington. Other states such as Tennessee and Kentucky reported the use of AOP design when a stream crossing affected habitat for federally-listed darters, dace, and madtom fish species. Other federally-listed aquatic organisms that may be of concern include mussels and salamanders.

Figure 1: "Stakeholder Respondents by State"



The responses also indicated that State DOTs are also seeking to comply with Clean Water Act Section 404 permit regulations, and specifically the Aquatic Life Movement general conditions that apply to Nationwide Permits. The aquatic life movement condition states “No activity may substantially disrupt the necessary life cycle movements of those species of aquatic life indigenous to the waterbody, including those species that normally migrate through the area, unless the activity's primary purpose is to impound water. All permanent and temporary crossings of waterbodies shall be suitably culverted, bridged, or otherwise designed and constructed to maintain low flows to sustain the movement of those aquatic species.” While this general conditions does not specify the use of specific culvert or bridge designs, or aquatic organism passage design methods, it does address the goal of restoring or maintaining effective aquatic organism passage.

Several state regulatory agencies (MA, MN, NY, TN, and WA) have developed permit requirements and/or guidance that require applicants to incorporate AOP design measures into roadway stream crossings (new and replacements). The guidelines generally include some flexibility in design and structure selection to account for site constraints (ROW, utilities), stream type, potential hydraulic trespass (flood elevation changes), and in one case (MN), to purposely exclude the use of AOP designs where invasive fish species are present and need to be confined.

Additional drivers identified by survey participants include meeting resource agency requirements for road crossing projects on federal lands. For instance, the National Park Service (NPS), Bureau of Land Management (BLM), and local DOTs working on federal lands follow either the USFWS stream simulation method or the HEC26 approach to design AOP compliant crossings. In addition, several NGOs (American Rivers, Trout Unlimited, and The Nature Conservancy) are reportedly active in watershed restoration activities with the USFWS and US Forest Service, utilizing grant funding from USFWS and state agencies to conduct watershed inventories and AOP assessments of culverts that drive crossing retrofits and replacements.

3.1.2 AOP Design Methods Utilized by State DOTs and Other Agencies

Based on the survey responses, AOP designs for stream crossings implemented by states and federal agencies vary in practice, but fall within one of three categories listed below.

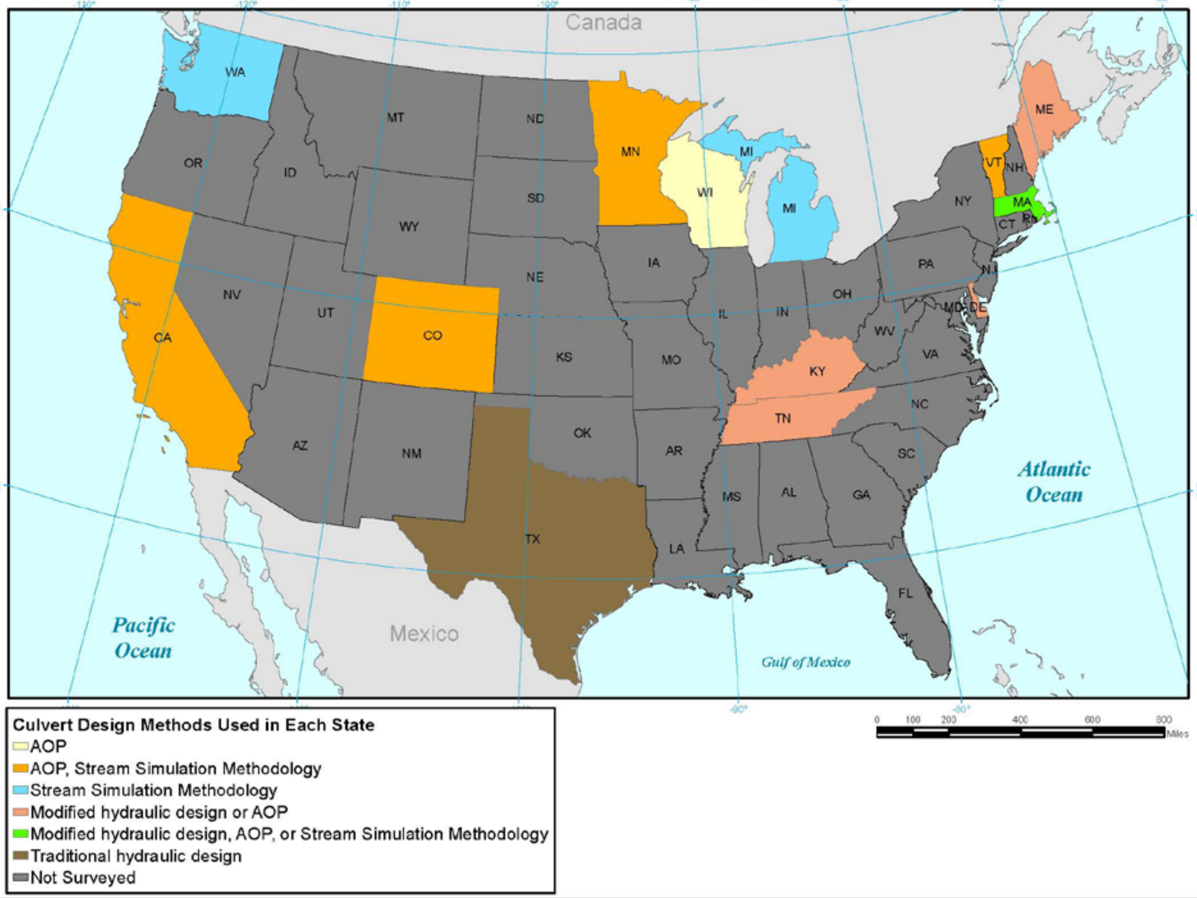
- *Stream simulation design (geomorphic design):* Culvert or bridge designed with hydraulic, sediment transport and stream geomorphology criteria taken into account to mimic functions of a natural stream and floodplain to maximize stream continuity. This approach is used by the USDA Forest Service (USFS), USDA Natural Resource Conservation Service (NRCS), USFWS, and several state DOTs, especially when addressing stream crossings affecting federally listed aquatic species. MnDOT follows this process in principle with their MESBOAC approach (Match, Extend, Set, Bury, Offset, Align, Consider) as detailed by MnDNR (2011).

- *Aquatic organism passage (AOP) design (HEC-26 and bankfull width times a safety factor):* Culvert or bridge designed with hydraulic, sediment transport and habitat criteria taken into account to facilitate passage of fish and other aquatic species. This approach typically leads to a smaller crossing width than under stream simulation. This approach is used by several DOTs.

- *Modified Hydraulic Design:* Culvert or bridge designed with hydraulic and practical structural criteria taken into account, and incorporates bankfull channel width and imbedded culverts or open bottom culverts with appropriate channel slope and channel bed substrates. This approach is used by several DOTs.

Figure 2 depicts the culvert design methods used in each of the states responding to the survey. As shown, several states utilize a mix of a modified hydraulic design, AOP design (HEC 26 and bankfull width) or stream simulation for stream crossing design, and two states were identified as using stream simulation as the primary approach to stream crossing designs.

Figure 2: Culvert Design Methods Used in Each Responding State



3.1.3 Project Costs

The initial surveys resulted in the identification of 90 stream crossing projects that involved the installation of bridges, culverts, and pipe structures that support aquatic organism passage. The data set was sorted by structure type and reviewed for the quality and completeness of the data. It should be noted that the project data from respondents in response to the initial inquiry varied in completeness and source, requiring additional inquiries will be made to gather more detailed project information. Additional sources of potential project cost data were provided during the interview phase.

Some of the project data are derived from literature sources, including a cost analysis of culvert installations practices in Minnesota that compared construction cost differences of AOP designed culverts versus standard hydraulic designs (Hansen et al 2009), an economic analysis of road crossing improvements in New York (Levine 2013), and an analysis of the cost effects of flooding and culvert performance following Tropical Storm Irene in Vermont (Gillespie et al 2014).

Only a handful of papers have made cost comparisons between AOP designed stream crossings and traditional hydraulic design stream crossings, and Levine (2013) provided a summary of the available comparisons. Table 2 presents a set of cost comparisons from a variety of regions of the country that collectively show that AOP design culverts have a construction cost increase over in-kind replacement or traditional hydraulic design.

Table 1. Installation Cost Increase of Improved Road-Stream Crossings Compared With In-Kind Replacement Costs (Source: Levine 2013).

Location	Mean % cost increase for improved crossing (range of values)	Notes
Green Mountain National Forest, Vermont	14% (9% - 22%)	Compares stream simulation culvert costs with cost of replacement based on hydraulic design
Minnesota (statewide)	10% (1% - 33%)	Compares cost of replacing existing culvert with improved “MESBOAC” design; costs considered are those of structures only
Maine (statewide)	Mean not available (80% - 295%)	Improved culvert widths in this study are 200% to 300% that of existing culvert
Tongass National Forest, Alaska	17% (-5% - 38%)	Compares stream simulation culvert cost with hydraulic design cost; stream simulation culverts are 25% - 83% wider than hydraulic design culverts; cost increase insignificant for streams of slope less than 3%
Oyster River Watershed, New Hampshire	42% (24% - 75%)	Compares cost to upgrade undersized culverts for a range of climate change/ precipitation change scenarios and land use scenarios with cost of in-kind replacement

Through the interview process DOT respondents consistently indicated that cost data for culvert maintenance activities is not tracked as separate cost items. In addition, other cost items associated with factors such as time delays, reduced permit review times, lost or gained recreational benefits, and risk reduction benefits from potential culvert failures are not readily available for their projects. While these types of benefits are discussed in recent literature (Levine 2013, Gillespie et al 2014), actual cost estimates for these benefits have not yet been found in the literature. In addition, life cycle costs of culverts that include an examination of long-term maintenance costs also appear to be lacking.

A cost-benefit analysis of the replacement of traditional hydraulic designed culverts with stream simulation culverts was recently performed for the Wisconsin Department of Natural Resources (WDNR) (Christiansen et al 2014). A total of 495 culverts were examined as part of the analysis which estimated fiscal benefits of increased project lifetime, reduced wetland impact, increased fish passage, reduced road user and maintenance costs, reduced flood damage and culvert failure rates, improved water quality and incremental installation cost. The report concluded that a net fiscal benefit of -$4,500 and average net social benefits of $7,800 per culvert replacement could be obtained on average. The report concludes that approximately 44 percent of culvert replacements yield a net fiscal benefit and 77 percent yield a net social benefit.

3.1.4 Long-Term Maintenance Costs

As noted above, long term maintenance costs for AOP design culverts are generally not collected by DOTs which complicates the development of a life cycle cost estimates and to draw a comparison between maintenance activities at traditional versus AOP culverts. AOP culverts also have a relatively short history and long term assessments of performance are generally not available. Some of the most recent data regarding AOP culvert performance have been derived from empirical evidence from field inspections following major storm events. Gillespie et al (2014) reported on the performance of two stream simulation designed stream crossings versus traditional hydraulic designed culverts in the White River watershed in Vermont following record flooding caused by Tropical Storm Irene in 2011. Additional comparative data may be available from other regions of the U.S.; one interview respondent provided anecdotal evidence of similar AOP crossing performance in Minnesota following a record rainfall event.

3.2 Follow-Up Interviews

After the review of the initial survey results, participants were contacted to determine if they had additional construction or maintenance life cycle cost information on the projects provided. Through this process the project list was refined to include only projects with sufficient information with which to prepare cost comparisons. A summary of the follow-up interviews is provided below.

3.2.1 Road Crossing Project Information

Participants from six DOTs, a federal and a state resource agency, a County agency and a non-profit organization provided project information on 74 AOP designed road crossings. The project data was reviewed and filtered for completeness of data and supporting background information such as the source of cost data (estimate or bid), date of cost estimate or contract bid, and structure descriptions. In several cases insufficient project cost data was provided and in two cases the crossing type was untypical (i.e., stone ford, or an all wood bridge structure) of most road crossing structures; these projects were excluded from the database. Table 2 provides a summary of the respondents and the number of projects by crossing and structure types.

Table 3 provides a summary of the 65 crossing types, the number of projects within each structure category, and the range and average estimated total cost, adjusted as needed to 2014 values.

Table 2: Summary of projects provided by responding DOTs and other agencies.

Contact Agency	Culvert Type	Culvert Description	Total
American Rivers	Pipe	Metal arch	1
Delaware Dept. of Transportation	Box Culvert	3-sided box	2
Delaware Dept. of Transportation	Box Culvert	4-sided box	3
Delaware Dept. of Transportation	Bridge	Concrete	2
Delaware Dept. of Transportation	Pipe	Concrete pipe	2
MA Division of Ecological Restoration	Box Culvert	3-sided box	2
MA Division of Ecological Restoration	Box Culvert	4-sided box	1
MA Division of Ecological Restoration	Bridge	Wood	1
MA Division of Ecological Restoration	Pipe	Metal arch	6
MA Division of Ecological Restoration	Pipe	Metal Pipe	2
MA Division of Ecological Restoration	Box Culvert	4-sided box	1
MA Division of Ecological Restoration	Pipe	Metal Pipe	1
MA Division of Ecological Restoration	Pipe	Metal arch	2
Maine Dept. of Transportation	Box Culvert	4-sided box	2
Maine Dept. of Transportation	Pipe	Concrete pipe	3
Massachuesetts Dept. of Transportation	Box Culvert	3-sided arch	2
Massachuesetts Dept. of Transportation	Box Culvert	3-sided box	3
Minnesota Dept. of Transportation	Box Culvert	4-sided box	10
Minnesota Dept. of Transportation	Pipe	Concrete pipe	1
Ozaukee, WI Planning and Parks Dept	Box Culvert	4-sided box	2
Ozaukee, WI Planning and Parks Dept	Box Culvert	Aluminum 3-sided box	1
Ozaukee, WI Planning and Parks Dept	Box Culvert	Aluminum 4-sided box	1
Ozaukee, WI Planning and Parks Dept	Pipe	Metal arch	1
US Forest Service	Pipe	Metal Pipe	12
Washington Dept. of Transportion	Box Culvert	3-sided box	8
Washington Dept. of Transportion	Box Culvert	4-sided box	2
Grand Total			**74**

The project data is most representative of northern latitude states where AOP design projects have a history of design and installation that has been spurred on by consent orders under the Endangered Species Act (ESA) for salmonids (i.e., Washington and Maine). The project costs were categorized by culvert structure type (pipe or box culvert), material (metal or concrete), form (3-sided or 4-sided box; arch or pipe) and length. In general, metal structures are cheaper to purchase and install than a comparably sized concrete structure which typically requires concrete support appurtenances (footings and wingwalls), though variations occur based on design. However, the service life of metal structures, even with treatment and use of concrete footers to extend their life, is still estimated at 50 years (Potter et al. 1991, cited by USDA USFS 2012). Other cost items within the total cost value include design and permitting fees, ROW acquisition, and construction costs.

Table 3: Summary of AOP road crossing total project cost (design, permitting and construction) data by crossing structure type, adjusted to 2014 dollars.

			Total Cost				Date of Cost Estimate	
Culvert Type	**Culvert Description**	**Total**	**Min**	**Max**	**Average**	**Median**	**Min**	**Max**
Box Culvert		33	$38,971.90	$2,911,600.20	$696,670.22	$406,036.10	2008	2014
Box Culvert	3-sided arch	1	$1,473,832.15	$1,473,832.15	$1,473,832.15	$1,473,832.15	2012	2012
Box Culvert	3-sided box	12	$204,382.20	$2,911,600.20	$1,213,665.40	$1,008,382.11	2008	2013
Box Culvert	4-sided box	20	$38,971.90	$1,244,249.04	$347,615.01	$144,966.52	2009	2014
Pipe		32	$21,757.32	$610,338.00	$220,396.03	$158,244.23	2006	2014
Pipe	Aluminum 3-sided box	1	$71,183.54	$71,183.54	$71,183.54	$71,183.54	2010	2010
Pipe	Aluminum 4-sided box	1	$128,193.81	$128,193.81	$128,193.81	$128,193.81	2010	2010
Pipe	Concrete pipe	5	$24,607.00	$307,158.27	$222,865.50	$254,794.73	2009	2014
Pipe	Metal arch	10	$179,130.36	$610,338.00	$401,561.93	$388,007.38	2006	2014
Pipe	Metal Pipe	15	$21,757.32	$560,626.00	$114,889.93	$61,794.72	2006	2014
Total		**65**	**$21,757.32**	**$2,911,600.20**	**$459,232.78**	**$230,629.30**	**2006**	**2014**

The data was also summarized based on regional distribution. Table 4 presents the average culvert cost by culvert type and region, as well as the number of projects from each region.

Table 4: Summary of AOP road crossing cost data by crossing structure type and by region, adjusted to 2014 dollars.

Midwest			Total Cost				Date Range of Cost Estimates		
Culvert Type	**Culvert Description**	**Total**	**Min**	**Median**	**Max**	**Average**	**Min**	**Median**	**Max**
Box Culvert		12	$38,972	$85,425	$207,464	$92,548	2009	2009	2012
Box Culvert	4-sided box	12	$38,972	$85,424	$207,464	$92,548	2009	2009	2012
Pipe		4	$24,607	$99,689	$591,734	$203,929	2009	2010	2013
Pipe	Aluminum 3-sided box	1	$71,184	$71,184	$71,184	$71,184	2010	2010	2010
Pipe	Aluminum 4-sided box	1	$128,194	$128,194	$128,194	$128,194	2010	2010	2010
Pipe	Concrete pipe	1	$24,607	$24,607	$24,607	$24,607	2009	2009	2009
Pipe	Metal arch	1	$591,734	$591,734	$591,734	$591,734	2013	2013	2013
Grand Total		16	$24,607	$85,424	$591,734	$120,394	2009	2009	2013

Northeast			Total Cost				Date Range of Cost Estimates		
Culvert Type	**Culvert Description**	**Total**	**Min**	**Median**	**Max**	**Average**	**Min**	**Median**	**Max**
Box Culvert		14	$204,382	$650,332	$1,788,148	$784,732	2008	2011	2014
Box Culvert	3-sided arch	1	$1,473,832	$1,473,832	$1,473,832	$1,473,832	2012	2012	2012
Box Culvert	3-sided box	7	$204,382	$508,054	$1,788,148	$858,456	2008	2010	2011
Box Culvert	4-sided box	6	$221,716	$631,089	$962,000	$583,870	2009	2012	2014
Pipe		19	$123,940	$282,433	$610,338	$303,870	2006	2013	2014
Pipe	Concrete pipe	4	$245,335	$268,614	$307,158	$272,430	2013	2014	2014
Pipe	Metal arch	9	$179,130	$385,191	$610,338	$380,432	2006	2013	2014
Pipe	Metal Pipe	6	$123,940	$144,240	$560,626	$209,987	2009	2012	2014
		33	$123,940	$336,404	$1,788,148	$500,775	2006	2013	2014

Northwest			Total Cost				Date Range of Cost Estimates		
Culvert Type	**Culvert Description**	**Total**	**Min**	**Median**	**Max**	**Average**	**Min**	**Median**	**Max**
Box Culvert		7	$859,444	$1,244,249	$2,911,600	$1,556,185	2013	2013	2013
Box Culvert	3-sided box	5	$859,444	$1,789,979	$2,911,600	$1,710,958	2013	2013	2013
Box Culvert	4-sided box	2	$1,094,253	$1,169,251	$1,244,249	$1,169,251	2013	2013	2013
Pipe		9	$21,757	$34,531	$165,630	$51,492	2006	2006	2006
Pipe	Metal Pipe	9	$21,757	$34,531	$165,630	$51,492	2006	2006	2006
Grand Total		16	$21,757	$113,713	$2,911,600	$709,795	2006	2006	2013

3.2.2 Classification of roadway crossing structures

Each crossing structure was initially classified based on the type of structure as described in the project material received from the participants. This information was cross-checked with any supporting documentation received such as plan sets, bid tables, and reports and any discrepancy was resolved with the source of the information. Since AOP structure cost was the primary concern and the cost of the structure varied based on structure material and construction requirements for footings and other attendant features, each project was further organized based on structure type (pipe or box),material construction (concrete, metal or wood), and length of structure. The culvert span length will be examined as a variable influencing project cost and included in the benefit-cost analysis.

Cost information for only 3 clear span bridge structures were provided by respondents. Given the small sample size, these types of bridge crossings were not advanced to the benefit-cost analysis since a meaningful comparison cannot be made.

3.2.3 DOT Experience with AOP Culvert Design and Installation

Through the follow up interviews, two of the six DOTs noted that they have been installing AOP culverts for over ten years with over hundreds of new culverts and culvert replacements installed. Some of these DOTs are over the learning curve for design, permitting and regulatory coordination and have experienced a reduction in overall project cost and permit review times as the process has become more streamlined and familiar to designers and regulators. Other DOTs also noted that the consulting industry is still on the learning curve in their region and that they expect the design costs for outside consultants to start to decrease over time to reflect growing familiarity with design requirements. The degree of experience within the industry will be reflected in the cost estimates received, particularly or older projects in regions with less experience. Some respondents also noted that they are actively engaged with the United States Forest Service (USFS) to facilitate training opportunities.

3.2.4 Risk Reduction and Reduced Maintenance Cost Factors and DOT Design Decisions

DOTs responding to the interviews had not incorporated the risk reduction (resiliency from large storm events) and reduced maintenance costs benefits, as documented by USFWS (Hendrickson 2008, USFS 2008), into a formal decision making process for culvert designs. Rather, these factors are part of an informal decision making process when assessing design and cost considerations for a project. There is some variability in practice for state DOTs. One state DOT indicated that while risk reduction and reduced maintenance costs may be considered conceptually, these are not factors when making design decisions as these factors are not common issues affecting the long term performance of highway culverts in their state. Another state DOT indicated that resiliency is now considered in culvert designs and they have recognized the need to accommodate larger flood events at a higher frequency and size structures accordingly. They have also moved away from the use of steel structures, including steel structures set on concrete abutments, due to the reduced longevity of material due to corrosion.

Washington State DOT noted that litigation has dictated that the USFS and Washington Department of Fish and Wildlife (WDFW) stream simulation method be employed for the replacement of 800 highway culverts by 2030. The use of the USFS/WDFW stream simulation method to set culvert sizes presumably accommodates both risk reduction and reduced maintenance cost factors since the method typically recommends a larger culvert size. They also noted that new and replacement culverts are designed on a site-by-site basis. Watershed characteristics, past performance history and type of proposed infrastructure are factored into the design of water crossings which will be sustainable for the structures design life.

3.2.5 Educational, Institutional, Legal, Technical, and Economic Barriers to AOP Based Designs versus Traditional Design Approach

DOT responses identified four types of barriers to the use of AOP designs, including education, legal requirements, technical issues, and funding. Each of these items is described below.

- Educational Barriers: Lack of familiarity with the AOP design process within the private and public sector leads to less efficient implementation of the design process and higher design costs. There may also be less acceptability of AOP designs by the public/local community due to unfamiliarity with the concept and the higher cost of implementation. Such cultural barriers could result in delays in project implementation.
- Technical Barriers: A potential technical barrier identified by some DOTs is the locally approved No-Rise Certification requirement, and the FEMA approved Conditional Letter of Map Revision (CLOMR) process. The No-Rise Certification requires the demonstration that the culvert design will not result in an increase in the downstream 100-year water surface elevation and in hydrologic impacts to downstream properties. The CLOMR provides FEMA comment on the extent of modification to the existing regulatory floodway, the effective Base Flood Elevations (BFEs), or the Special Flood Hazard Area (SFHA). The minimum time to receive FEMA approval is 90-days. If the use of an AOP culvert increases the FEMA flood elevation downstream of the culvert such that adjoining properties are affected, then a floodplain easement will be required to compensate the landowner for the encumbrance of their property due to an expanded floodplain limit. The required easements would introduce significant ROW acquisition costs to the project as well as extend the project schedule.
- Technical Barriers: Roadway geometry, ROW limits, and utilities each influence the height and width of a structure that can be used at a crossing, and the overall project cost. Right-of-way width, utilities and highway geometry are factors that can influence allowable size of structure. Height restrictions on a culvert structure may be due to road surface elevations or roadway curvature. The hydrologic function of the culvert also needs to consider the potential effect of connected culvert systems such that the new/replacement culvert does not interfere with function of downstream culvert. Each of these elements also affects the cost of the project which is another potential barrier for use of an AOP design crossing.
- Funding Barriers: Funding for culvert replacements with AOP culvert designs was consistently identified as a significant barrier. While DOTs recognize that current regulations require the use of an AOP culvert design, the higher costs of these projects limit the number of replacements

that can be conducted annually, and can affect budget expenditures for other roadway maintenance programs.

3.2.6 Cost of Individual Maintenance Actions

As noted in the Task 2 memo report, DOT respondents to the initial survey consistently indicated that cost data for culvert and long term maintenance activities is not tracked as separate cost items. As part of the second interviews, the request for additional information was pursued and only limited information was provided or available from DOTs. Generally, each DOT district or region has a separate operating budget that covers maintenance costs. DOTs also noted that the limited annual budget for maintenance activities covers culvert cleaning (sediment and debris removal) and culvert replacements for smaller structures (e.g., up to 48-inch diameter). Respondents consistently stated that maintenance costs for culverts are typically not tracked as separate costs by DOTs. From the limited data received, an estimate of maintenance costs per culvert per event ranged from $800 - $1200.

As noted previously, Christiansen et al (2014) developed an estimate of lifetime maintenance cost savings for conventional and stream simulation designed culvert based on a dataset of 1,615 culverts in Green Bay, Wisconsin. As part of that study, average maintenance costs for an undersized (non-AOP design) culvert was estimated at $748 per event to clean sediment from a single culvert. Of the 1,065 culverts in the dataset, only 10% indicated the presence of an obstruction (Christiansen et al 2014). From the dataset the researchers derived an average total maintenance cost for a conventional culvert with a 35-year lifespan of $2,585.

An additional report was released in 2015 (MA DER, 2015) that examined the economic and community benefits of three culvert replacements that were upgraded to meet AOP standards. For these projects, an estimated maintenance costs was developed that covered debris removal, rip-rap replacement, and minor road repairs over the life of the existing, undersized culverts which are subject to frequent high flows and potential damage. The total maintenance costs ranged from $9,000 and $24,000 per culvert over the expected life of the culverts (25 years for pipe and 50 years for a concrete box).

Table 5 presents a set of cost comparisons from a variety of regions of the country that collectively show that AOP design culverts have a construction cost increase over in-kind replacement or traditional hydraulic design.

4.0 Benefit-Cost Model

In order to draw a comparison between the benefits and costs of AOP culverts versus traditional hydraulic design culverts, a standard benefit-cost analysis (BCA) was performed using the data set of 65 projects. The benefit-cost analysis model was expanded to incorporate economic benefits and costs that go beyond a traditional financial evaluation. The step factors in financial benefits address potential benefits from reduced maintenance costs and a longer functional lifetime of structures, potential cost savings (avoided costs) related to structure failures during extreme flow events, and environmental and social benefits like recreational use and habitat connectivity. These benefits come with the increased capital costs associated with the use of larger structures to achieve functional AOP designs.

Table 5: Summary of Recent Analyses of Construction Cost Comparisons between Traditional Hydraulic Culverts (HC) Versus AOP Culverts

Source	Location	Number of Projects	Findings
Minnesota DOT (Hansen et al, 2009)	Minnesota	11	AOP culvert cost -3% to +33% compared to HC design estimate. Most of cost difference driven by increased size of structures
Wisconsin DNR (Christiansen et al, 2014)	Wisconsin	495	Cost-Benefit analysis for AOP culvert replacements; net fiscal benefit -\$4700/culvert; net social benefit \$7800/culvert.
Gillespie, et al, 2014	Vermont	3	AOP culvert cost +9% to +12% higher than HC design estimate
MA DER, 2015	Massachusetts	3	Long term average cost savings for AOP culvert installation relative to in-kind replacement: Range: -\$41K, +\$190K and +\$520K[1]

Note: [1]-Each project provided a significant savings to local municipalities by reducing burden of cost share by qualifying for additional funding by using AOP culvert designs.

Economic analysis is important for projects that involve public goods because their benefits go beyond those that are merely captured by projected design and construction costs. Benefits can be difficult and costly to measure; therefore, the model focuses on measuring those benefits most directly related to the project and using readily available data. The benefits represent the project's most direct economic impacts. All benefits considered are incremental which means that only net increases in the benefit compared to the costs are considered.

In addition, a sensitivity analysis was performed on the results using the Monte Carlo simulation. The Monte Carlo simulation is implemented through use of the @Risk add-on to Microsoft® Excel® available from Palisade Software. Simulations on the costs and benefits are conducted and each simulation is composed of ten thousand iterations. This number of simulations is sufficient to promote stability and consistency in the output values should simulations be repeated with identical input values. In an iteration, the software randomly draws a single point estimate from input probability distributions for each budget line item, drawing from the median, low and high estimates according to the probabilities represented in the shape of the input distributions (e.g., values greater than the 90 percent confidence interval are selected only 10 percent of the time). Line items are then summed to estimate the total cost for each iteration. A probability distribution for the output measure (total cost) is based on the totals calculated for each of the ten thousand iterations in a simulation.

4.1 Model Assumptions and Variables

The BCA model provides an analysis of the net benefits of using an AOP culvert design versus a traditional hydraulic design culvert. Unlike prior cost-benefit analyses which have used estimated installation costs for AOP culverts (Christiansen, 2014), this BCA model is using a set of actual cost data within the project database, and supplemented with values derived from relevant literature or engineers estimates.

Available data was used when possible and detailed and supported assumptions were used for other items. All assumptions are listed in the model so that sensitivity analysis or updates to input variables can be easily entered and tracked. A summary of the relevant assumptions and supporting reference information are described below.

Design, Construction and Operational Costs

Design and construction costs were derived from the database of project information for AOP design culverts. The design and construction costs of traditional hydraulic design culverts was derived from a several cost comparisons provided through the interviews, and supplemented through the development of engineers cost estimates of the replacement cost of existing structures when project comparative costs were not available. The engineers estimate is based on the available estimates, reports, construction item bids and design plans provided during the interviews. All cost information was normalized to 2014 costs. Table 6 provides a summary of the cost data for both the AOP and traditional design culvert structures used in the BCA model. The data are summarized by region. Operational costs are derived from both published sources, information from interviews and engineers estimates.

The traditional design replacement cost estimates for the 3-sided and 4-sided box culverts consist of a mixture of structure types (box culverts and large pipes) that are assumed to represent an acceptable traditional design alternative structure to the AOP culvert type. This approach is considered to provide a very conservative cost estimate (lower) for box culverts to compare with the AOP replacement culverts. The approach also represents a cost comparison based on a mix of replacement project conditions rather than a direct comparison of similar structure types. In addition, the seven traditional design culvert replacement cost examples from the northwest region have a much lower range and average costs than the corresponding AOP culverts. For 3-sided culverts in particular, the northwest projects compose 38% of the cost data which drives the average traditional design project costs much lower than would be obtained using just the project examples from other regions.

The BCA model incorporates the following cost factors:

- Increased Capital Costs (cost of installing more expensive structures and corresponding higher installation and replacement costs).
- Replacement costs (the cost to replace a structure at the end of its lifespan for an AOP structure versus a traditional hydraulic structure).
- Maintenance costs (cost to maintain structure opening/capacity, such as sediment and debris removal, and rip-rap stabilization replacement).

- Catastrophic loss cost (the cost to repair roadway and structure damage due to climate change driven risk of a flood event exceeding structure capacity over the structure lifespan).
- An inflation rate of 2.5% is assumed over the maximum period of 50 years.

Project Benefits

The benefits of AOP road crossings that are included in the BCA model can be grouped into categories of social, environmental, and economic benefits. Each category is outlined below.

- Social Benefits

Social benefits are derived from the safe roadways that provide the public with access to jobs, recreational opportunities, and needed services for health and wellbeing. The catastrophic loss or damage to a roadway culvert crossing a stream or river can disrupt access and potentially lead to injury or loss of life.

Table 6: Summary of cost data used in the BCA model.

Midwest			AOP Cost				Traditional Design Replacement In-kind[1]				Project Range
AOP Culvert Type		Total	Min	Median	Max	Average	Min	Median	Max	Average[2]	
Box Culvert		12	$38,972	$85,425	$207,464	$92,548	$32,117	$85,170	$212,000	$103,197	2009 to 2012
Box Culvert	4-sided box	12	$38,972	$85,424	$207,464	$92,548	$32,117	$85,170	$212,000	$103,197	2009 to 2012
Pipe		4	$24,607	$99,689	$591,734	$203,929	$22,196	$213,500	$337,000	$196,549	2009 to 2013
Pipe	Aluminum 3-sided box	1	$71,184	$71,184	$71,184	$71,184	$197,000	$197,000	$197,000	$197,000	2010
Pipe	Aluminum 4-sided box	1	$128,194	$128,194	$128,194	$128,194	$230,000	$230,000	$230,000	$230,000	2010
Pipe	Concrete pipe	1	$24,607	$24,607	$24,607	$24,607	$22,196	$22,196	$22,196	$22,196	2009
Pipe	Metal arch	1	$591,734	$591,734	$591,734	$591,734	$337,000	$337,000	$337,000	$337,000	2013
Grand Total		16	$24,607	$85,424	$591,734	$120,394	$22,196	$90,749	$337,000	$126,535	2009 to 2013

Northeast			AOP Cost				Traditional Design Replacement In-kind[1]				Project Range
AOP Culvert Type		Total	Min	Median	Max	Average	Min	Median	Max	Average	
Box Culvert		14	$204,382	$650,332	$1,788,148	$784,732	$56,000	$172,000	$1,045,000	$360,250	2008 - 2014
Box Culvert	3-sided arch	1	$1,473,832	$1,473,832	$1,473,832	$1,473,832	$823,000	$823,000	$823,000	$823,000	2012
Box Culvert	3-sided box	7	$204,382	$508,054	$1,788,148	$858,456	$56,000	$155,500	$1,045,000	$417,500	2008 to 2011
Box Culvert	4-sided box	6	$221,716	$631,089	$962,000	$583,870	$104,000	$177,000	$350,000	$199,000	2009 - 2014
Pipe		19	$123,940	$282,433	$610,338	$303,870	$16,000	$158,000	$326,000	$164,023	2006 to 2014
Pipe	Concrete pipe	4	$245,335	$268,614	$307,158	$272,430	$144,000	$243,000	$326,000	$239,000	2013 to 2014
Pipe	Metal arch	9	$179,130	$385,191	$610,338	$380,432	$16,000	$172,000	$240,000	$137,714	2006 to 2014
Pipe	Metal Pipe	6	$123,940	$144,240	$560,626	$209,987	$113,676	$129,894	$132,755	$125,442	2009 to 2014
		33	$123,940	$336,404	$1,788,148	$500,775	$16,000	$169,500	$1,045,000	$254,589	2006 to 2014

Northwest			AOP Cost				Traditional Design Replacement In-kind[1]				Project Range
AOP Culvert Type		Total	Min	Median	Max	Average	Min	Median	Max	Average	
Box Culvert		7	$859,444	$1,244,249	$2,911,600	$1,556,185	$10,000	$41,000	$80,000	$41,405	2013
Box Culvert	3-sided box	5	$859,444	$1,789,979	$2,911,600	$1,710,958	$10,000	$43,000	$80,000	$45,966	2013
Box Culvert	4-sided box	2	$1,094,253	$1,169,251	$1,244,249	$1,169,251	$22,000	$30,000	$38,000	$30,000	2013
Pipe		9	$21,757	$34,531	$165,630	$51,492	$21,970	$30,908	$103,212	$38,886	2006
Pipe	Metal Pipe	9	$21,757	$34,531	$165,630	$51,492	$21,970	$30,908	$103,212	$38,886	2006
Grand Total		16	$21,757	$113,713	$2,911,600	$709,795	$21,790	$34,607	$103,212	$39,988	2006 to 2013

Notes: 1- Traditional design costs are based on data provided by survey respondents or developed as part of engineers' estimates under this study of the replacement cost of existing traditional design culverts derived from design documents. See text for further explanation.

2 – For 9 of the 12 projects, the AOP culvert costs were between 1% and 29% percent higher than the traditional design. Two AOP culverts had costs much lower than the traditional design cost estimate which affected the average and median values.

The BCA model incorporates the cost factors outlined below based on economic values for the Northeast, Midwest and Northwest regions.

- Road User Delay Costs: Floods can cause delays for road users that will have a social and economic implication due to the additional time spent in a car due to detours and added traffic congestion. The costs associated with travel delays due to minor road flooding and culvert/road failures was estimated by region based on average annual daily traffic on local and rural roads apportioned between private (94%) and business travelers (6%), with an average of 1.67 persons per vehicle, which is consistent with the WDNR study (Christiansen, et al 2014). An estimated per hour cost of travel was also calculated by region for private and business travels and adjusted based on an average delay of 30 minutes over a 14 day closure period for roadway repair following a culvert failure. Temporary closure of roadways due to over-topping by floodwaters for one to two days and the associated minor road user delay costs was not included in the BCA as a separate cost item.

- Avoided Health Impacts: The cost of injury (treatment, rehab) associated with flooding impacts was based on 2008 national health cost for river flooding injuries and total number of people injured. The average cost per person was discounted to 2014 dollar values, and proportioned to each region based on total population distribution. The average annual cost of illness due to flooding was estimated at $1,350 per person, and the annual number of affected residents by region was calculated as: northeast, 33.8; midwest, 16.9; northwest, 16.9.

- Flood Events: For road user delays and avoided health impacts, it is assumed that minor flooding events will happen on average every 30 years for an AOP box culverts and every 15 for traditional design box culverts, and every 10 years for an AOP pipe culvert and every 5 years for traditional design pipe culverts. This allowed us to further estimate the value of time for a 3-sided box culvert, 4-sided box culvert, concrete pipe, and metal pipe culverts. It is important to note that every region will have roads with different traffic volumes. For instance, the Northeast has higher traffic volumes than other regions in the northern USA. In order to account for this, higher traffic ratios were used for projects in the Northeast.

- Recreation Benefits: The economic benefits are associated with the use of aquatic resources by humans for recreational purposes (fishing trips, tourism) are associated with improved fisheries habitat within reconnected stream segments upstream of the culvert. The dollar value is based on regional economic surveys of annual expenditures by fisherman and willingness-to-pay surveys for resource services. Based on the limited literature survey conducted it is apparent that there is a range of estimates that vary between regions and is generally driven by the presence of salmon species in the northwest and trout fishing in the Driftless region of the Midwest (NorthStar Economics, 2008). The northeast has high valued recreational fishing associated with trout; currently there is no open seasons for Atlantic salmon which is a federally listed endangered species. The annual per acre values reviewed for this study are listed in the table below along with the values used in the model, discounted to 2014 dollars, in bold.

Northwest		Midwest	Northeast
Low Value	High Value	Value	Value
\$2,475.18[1] (2012)	\$8,559[2] (2008) (**\$9448**)	\$9,369[3] (2010) (**\$10,342**)	\$356[4] (2006) (**\$434**)

Sources: Flores, Lola P. 2012[1]; Robbins, Jesse L. and Lynn Y. Lewis. 2008[2]; Charbonneau, Joseph J., Ph.D. and James Caudill, Ph.D. 2010[3]; Costanza, R., Wilson, M., Troy, A., Voinov, A., Liu, S., and D'Agostino, J. 2006[4].

The value for the northeast is considered to be conservative. While economic studies of the value of recreational activities in northeast states have been performed, including examining the annual contribution of fishing to state economy, the studies do not transform the values to a per acre measure of aquatic habitat. The estimated acreage of reconnected stream habitat was calculated using the method described under Aquatic Habitat Benefits described below.

- Environmental Benefits

Environmental benefits are associated with improved aquatic connectivity due to the installation of an AOP design crossing structure. Environmental costs are associated with the potential for flood events to cause non-catastrophic damage to culverts, roadway slopes and channel banks due to erosion. Both items are incorporated into the BCA model as described below.

- Aquatic Habitat Benefits: The aquatic habitat benefits are based the dollar value of ecosystem services derived from streams, expressed as \$/per acre/per year. The values were difficult to quantify due to an apparent lack of directly applicable studies for aquatic habitat connectivity, and variability in ecosystem value measurements for stream habitat across the different states/regions. For the purpose of comparison it was assumed that the pre-existing culvert had impaired fish passage to some degree. While the value for ecosystem benefits will be higher when populations of threatened or endangered species are present, for instance Pacific salmon in the northwest and Atlantic salmon and brook trout in portions of the northeast, a more conservative value was applied to represent what is expected to be the most common condition. The table below presents the annual contribution of ecosystem services from streams as dollar values per acre of aquatic habitat. The value in bold, discounted to a 2014 value, is used in the model.

Resource Type	Northwest	National	
	Value	Low Value	High Value
Aquatic Habitat	$317.20[1] (2012)	$331[2] (2010) (**$365**)	$8,947[3] (2010)
Salmon Habitat	$5,000[4] (2001)		

Sources: Flores, Lola P., 2012[1]; Ingraham, Molly W. and Shonda Foster, 2008[2]; Charbonneau, Joseph J., Ph.D. and James Caudill, Ph.D. 2010[3]; Gregory, R. and K. Wellman. 2001[4].

The amount of stream habitat upstream of the culvert was measured based on the linear stream distance between the project site culvert and either the next upstream culvert or the point where the observable stream channel width decreased to three feet in width. An average stream width was estimated at both the upstream and downstream ends of the stream channel and at a point away from the influence of the culvert. The acreage was estimated using the equation for the area of a trapezoid:

$$A = \frac{a+b}{2}h$$

Where: a = average stream width upstream
b = average stream width downstream
h = linear length of stream segment
A = acreage of stream habitat

- Flood Damage: Environmental costs associated with minor damage to culverts, roadway debris removal, and slope and stream bank stabilization due to erosion from events that cause flooding are treated as periodic costs spread out over lifespan of the structure. Minor flood damage repair by DOT or county maintenance crews is estimated at $950 per event which includes mobilization, wages, and contingency, and is multiplied by a factor of 4 to account for inflated costs for emergency repairs (Pherrin and Jhaveri, 2004), providing an estimated rate of $3800 per event. For comparison, the WDNR study (Christiansen et al, 2014) used a similar estimate of $2992.

  The probability of flood damage for box culverts is assumed to be 1 in every 30 years and for pipe culverts is 1 in every 10 years. A more frequent rate was used for pipe culverts due to the higher probability of debris accumulation that would exacerbate flood risk. In addition, a 0.4% incremental factor is added each year to account for climate change and a higher risk for an event that will cause flood damage.

- Economic Benefits

Economic benefits are derived from transportation services that connect the public and businesses to jobs and businesses to markets and other required infrastructure. Maintaining and replacing roadway culverts is required to maintain safe and functional transportation corridors. Routine maintenance of culverts, when multiplied by thousands of existing culverts across statewide road networks, is a significant budget item for DOTs and Counties. Local economies are also dependent on good transportation networks. The catastrophic loss or damage to a roadway culvert crossing of a stream can disrupt normal economic activities on a local or regional scale. Reducing the frequency for maintenance and reducing the risk for catastrophic culvert failures are examples of avoided costs that have the potential to be significant over the lifespan of a structure. The BCA model incorporates both of these avoided cost benefits into the analysis.

- Maintenance Costs: The cost of performing regular maintenance of culverts is a capital cost necessary to maintain the proper function and lifespan of a culvert. The removal of sediment and obstructions by DOTs and counties was accounted for in the BCA model using the following assumptions:
  - 1 Cleaning every 4 years for Traditional Design
  - 1 Cleaning every 8 years for AOP Design
  - Costs of $750 per 4 hours for a single event, including mobilization, wages.

  The higher frequency of maintenance efforts for traditional culverts design is based on the assumption that smaller sized structures will be more prone to the collection of debris and sediments.

- Catastrophic Failures and Replacement costs: The costs for culvert replacements due to a catastrophic event were adjusted based on the probability of such an event adopted from the WDNR (Christiansen et al, 2014) study which applied a probability of a flood event causing severe road damage and closure of 3% per year for box culverts. A higher probability of 10% per year for pipe culverts was assumed due to the smaller size of pipe openings and the higher probability for clogging by debris during a flood event. A climate change factor of 0.4% per year is included to account for an increased probability of a flood damaging event occurring each year.

Structure Type	Catastrophic Yearly Probability
AOP Box Culvert	**0.5%** (1 every 50 years, further reduced by 75% for reduced failure rate of AOP designs)
Traditional Box Culvert	**2.0%** (1 every 50 years)
AOP Pipe	**1.0%** (1 every 25 years, further reduced by 75% for reduced failure rate of AOP designs)
Traditional pipe	**4.0%** (1 every 25 years)

5.0 Findings

The BCA was completed using a 7% discount rate and a 50-year planning evaluation horizon. Using these parameters, the one-time design and construction costs and the lifetime costs and benefits to operate and maintain the culvert structures were calculated. In order to compare the two types of culvert designs we considered benefits and costs for each type of culvert and for AOP versus Traditional design. The formulas are:

- **Lifetime Costs = One Time Costs + Annual Costs**
- **Net Benefit/Costs = Lifetime Costs AOP Culvert – Lifetime Costs Traditional Culvert**

This can approximate and quantify the benefits that an AOP design can have over the long run that go beyond the capital costs. The model finds that the initial higher capital costs of the AOP design culverts are offset by higher benefits in the long period. Table 7 provides a summary of the lifetime costs and net benefit. The results of the analysis clearly show that for each structure type, the AOP structures cumulative present value of lifetime costs (benefits minus costs) is lower than that of the traditional design structure. For pipe culverts, the analysis included the cost to replace the structures after 25 years.

Figures 3a through 3b provide the breakout of the cumulative costs and benefits from each element of model over the 50-year period. As can be seen in the figures, the two drivers of the higher lifetime costs for traditional design culverts are the costs associated with higher risk of catastrophic failure costs and the higher risk of health effect costs due to flooding. The reduced costs for these elements for AOP design culverts represent avoided costs savings for AOP structures due to the lower risk attributed to the use of larger structures with a higher hydraulic capacity and ability to pass larger flows, sediment and flood debris.

Recreational benefits generally provide a moderate cost benefit to AOP design structures (represented as a negative value and thus discounted from total lifetime costs), and aquatic habitat benefits provide comparatively small cost benefits. Other elements not included in the BCA analysis could also provide possible cost savings for AOP structures such as reduced resource agency approval time frames or avoidance or reduction of additional mitigation measures.

It should be noted that project specific circumstances and regional conditions could significantly alter the cost factors for an individual culvert replacement project and result in a BCA result with different results. The development of standardized regional or state level BCA models may be more beneficial to transportation agencies to assess the benefits and cost of individual projects and aid in decision making.

Table 7: Summary of BCA estimate of lifetime costs and net benefits of AOP culvert project costs and Traditional Design culvert project costs over a 50-year period.

	Lifetime Costs Over 50 Years			
AOP Structure Type	**3-Sided Box Culvert**	**4-Sided Box Culvert**	**Concrete Pipe**	**Metal Pipe**
AOP	$4,534,076	$2,378,199	$3,045,468	$3,735,835
Traditional Design	$5,074,694	$2,726,067	$7,450,497	$4,967,583
Net Benefits	$540,618	$347,869	$4,405,029	$1,231,748

Sensitivity Analysis of Selected Parameters

Given that the model considers several intangible assumptions, we performed sensitivity analysis on a variety of them to see the impact on the net benefits. The most important of these variables is the capital cost. The model shows that for box culverts, the capital cost of the AOP design will reach a breakeven point at between 5 and 20 percent more than the considered capital cost value before the net benefits become a loss. The breakeven point of capital costs for metal pipes is around 50 percent more than the value considered.

Another sensitivity can be executed for useful life of the AOP designs. The lifespan of culverts was assumed as 50 years for a box culvert and 25 years for a pipe. Should the lifecycle of these AOP design culverts be lower, then the net benefits will decrease as more money would need to be spent to replace them in a shorter period of time. The breakeven point of useful life for boxes is calculated at 40 years before the net benefits become a loss. The breakeven point of useful life for pipes is estimated at 10 years before the net benefits become a loss.

Finally, an important factor affecting the cost benefit analysis are the benefits related to recreation and to natural habitat. The effect vary by type of culvert and by geographical region so it’s possible to have big swings in values. The analysis considered the values described in the previous section as base for recreational benefit. The largest effect is seen with the 3-sided box culverts. The sensitivity analysis on these values was run to estimate how much the benefit value can decrease but still have a positive overall benefit for AOP culverts. For the 3-sided box culverts, the benefit value could decrease up to 15%, and for the 4-sided box up to 50%. For the pipe culverts the overall effect is minimal compared to the capital costs. The same analysis was performed for the aquatic habitat benefits, but the effect on all AOP designs is not significant enough to affect the overall benefits by itself. However, if a higher value is applied as in the case of salmon habitat in the northwest ($5,000/per acre/year), than the added benefit would certainly have a much higher positive benefit for AOP designs.

Figure 3a: Total accrued costs for an AOP design 3-sided box culvert over a 50-year life span.

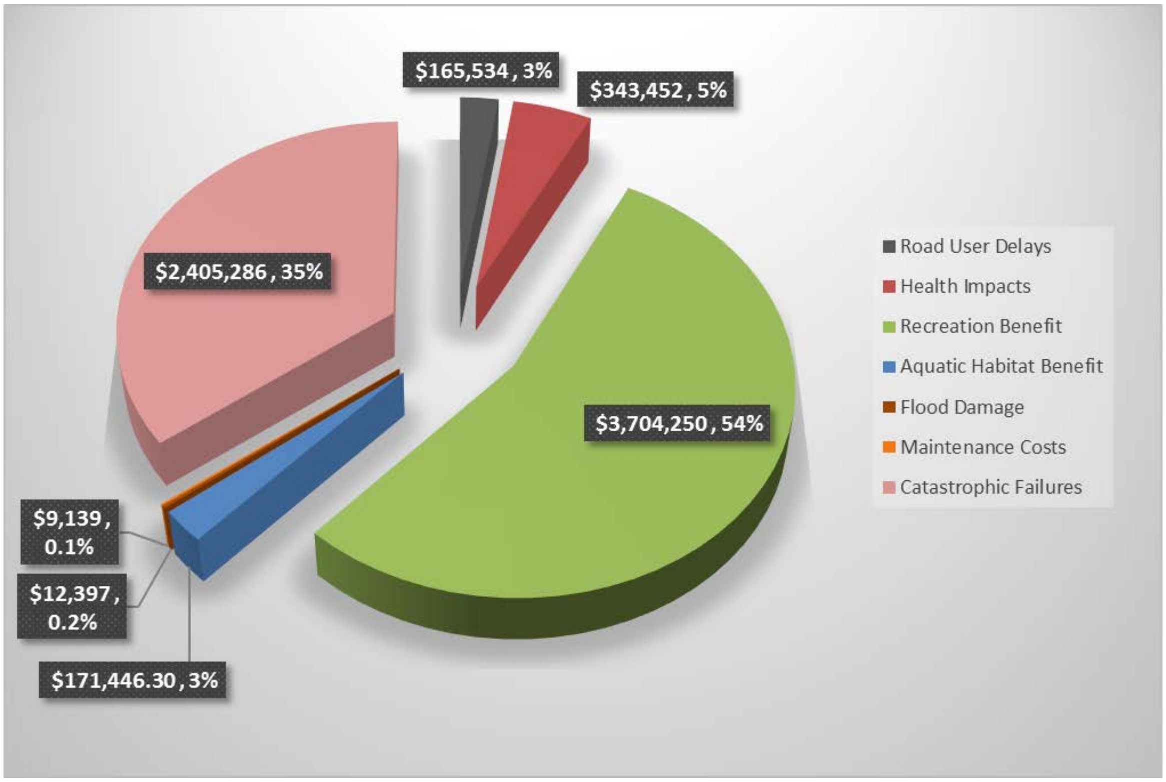


Figure 3b: Total accrued costs for a traditional design culvert over a 50-year life span.

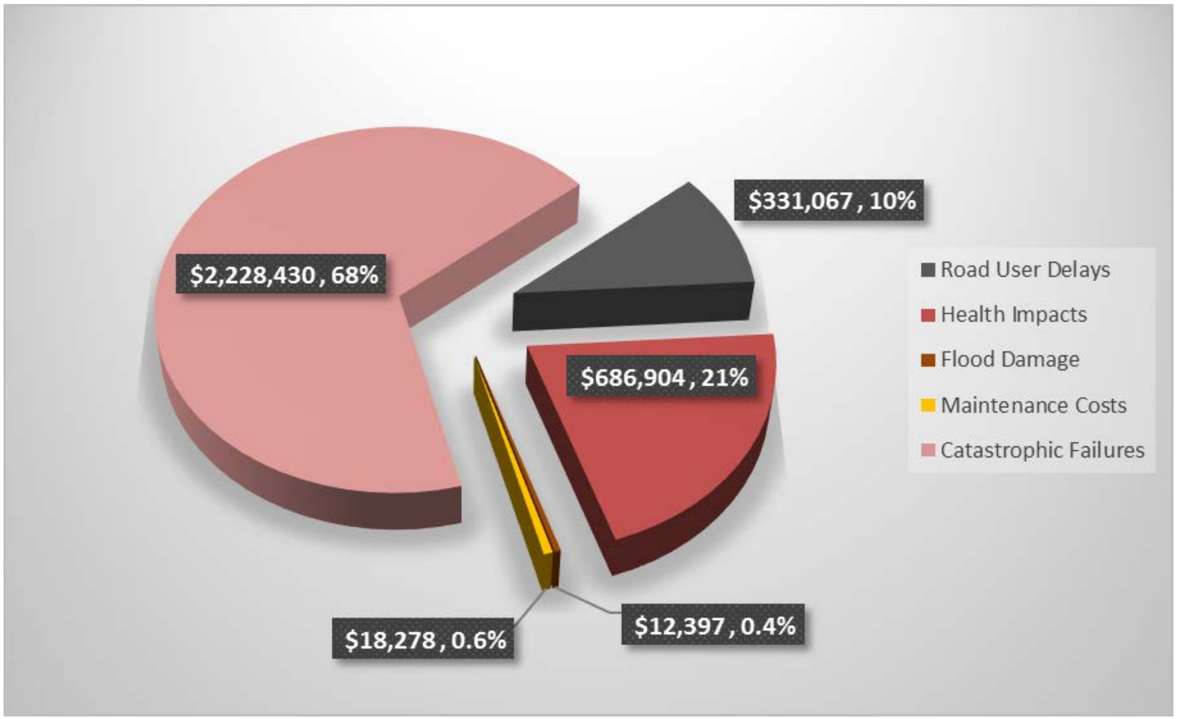


Figure 3c: Total accrued costs for an AOP design 4-sided box culvert over a 50-year life span.

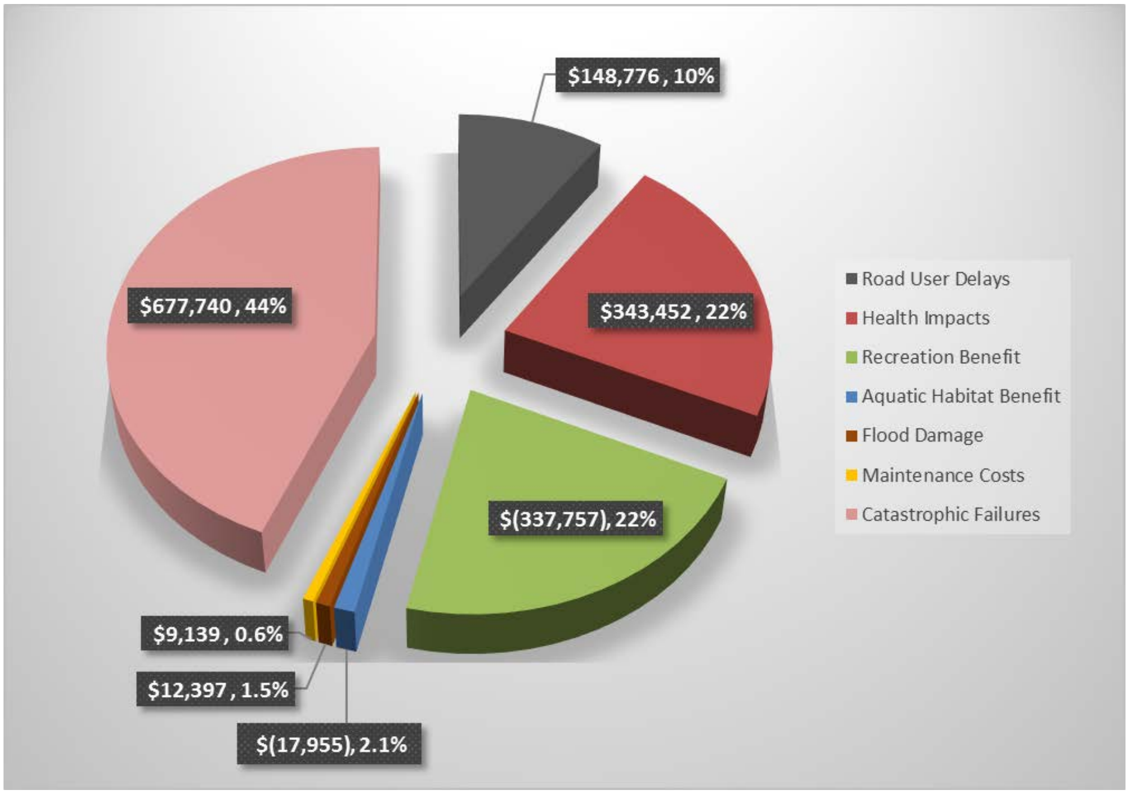


Figure 3d: Total accrued costs for a traditional design culvert over a 50-year life span.

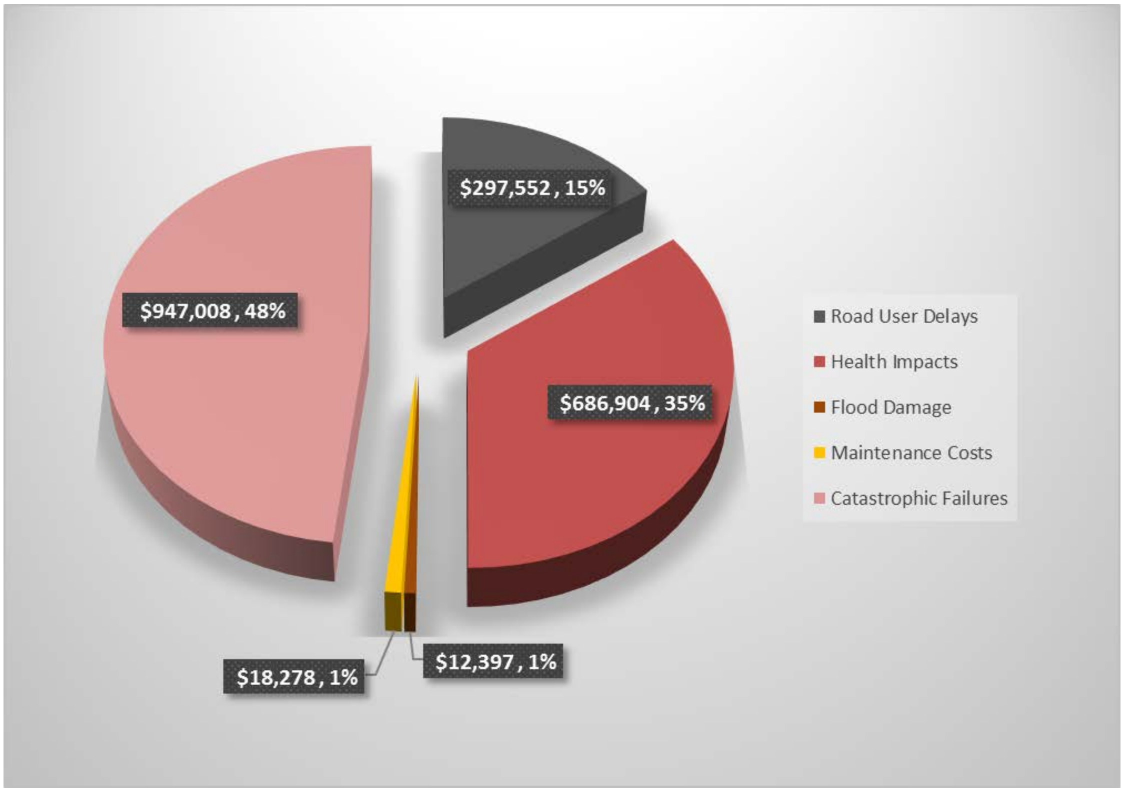
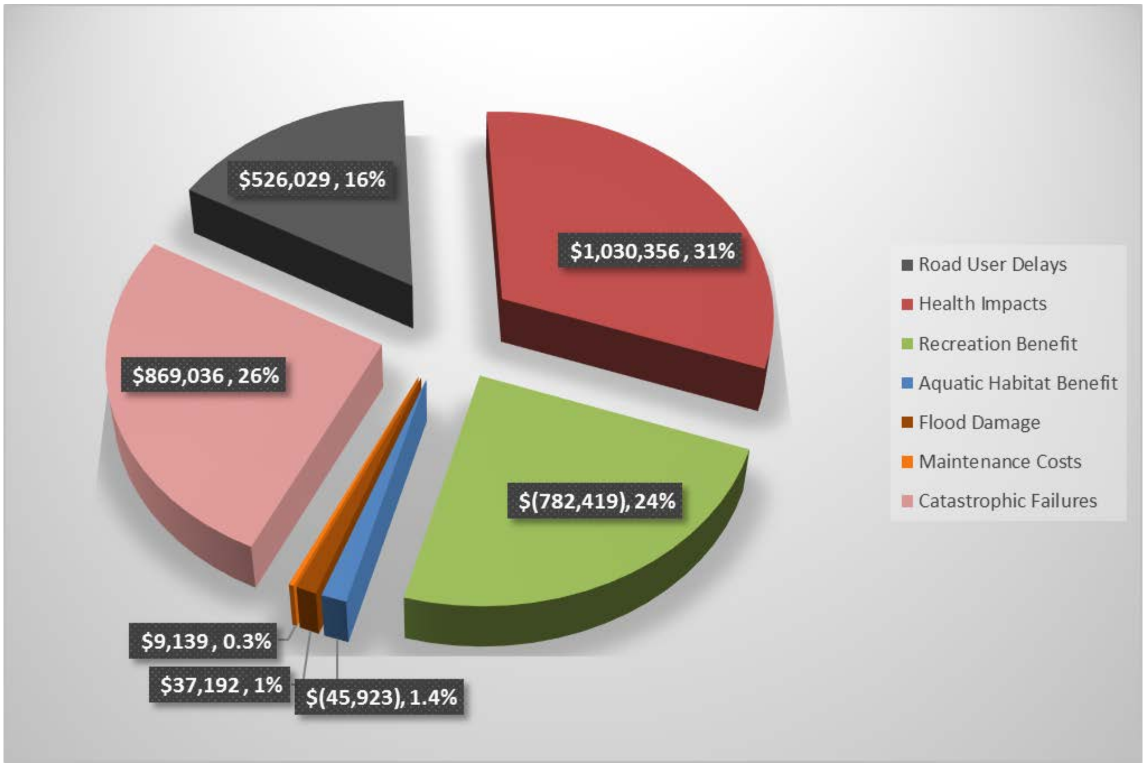


Figure 3e: Total accrued costs for an AOP design concrete pipe culvert over a 50-year life span.



igure 3f: Total accrued costs for a traditional design pipe culvert over a 50-year life span.

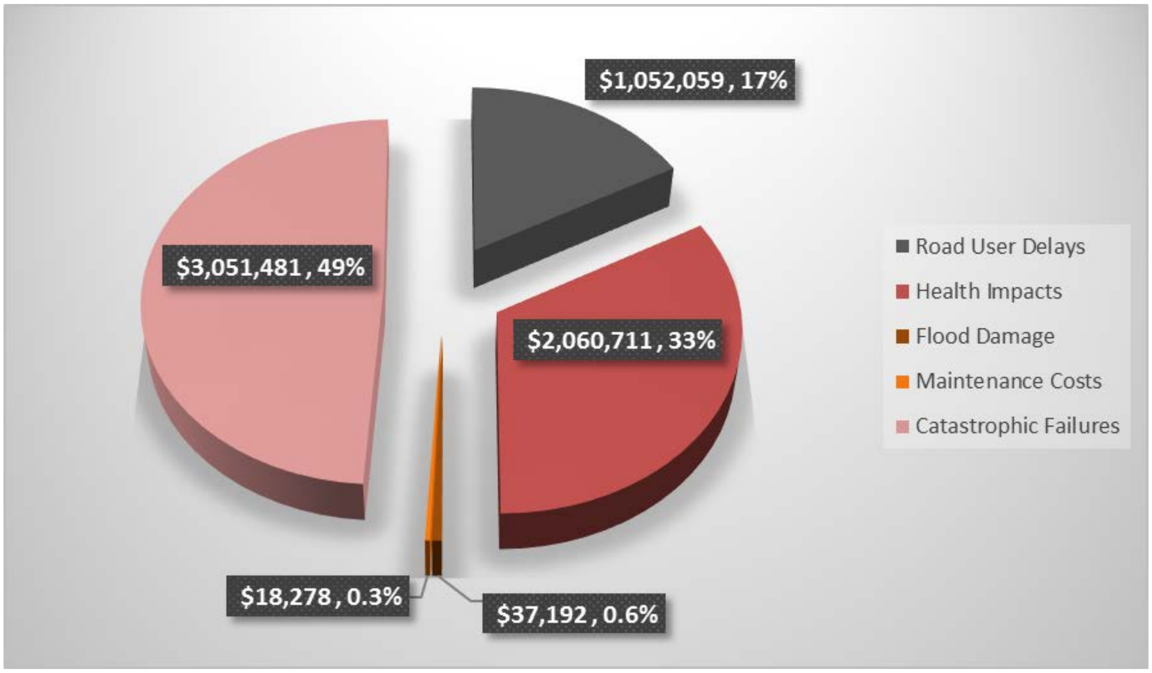


Figure 3g: Total accrued costs for an AOP design metal pipe culvert over a 50-year life span.

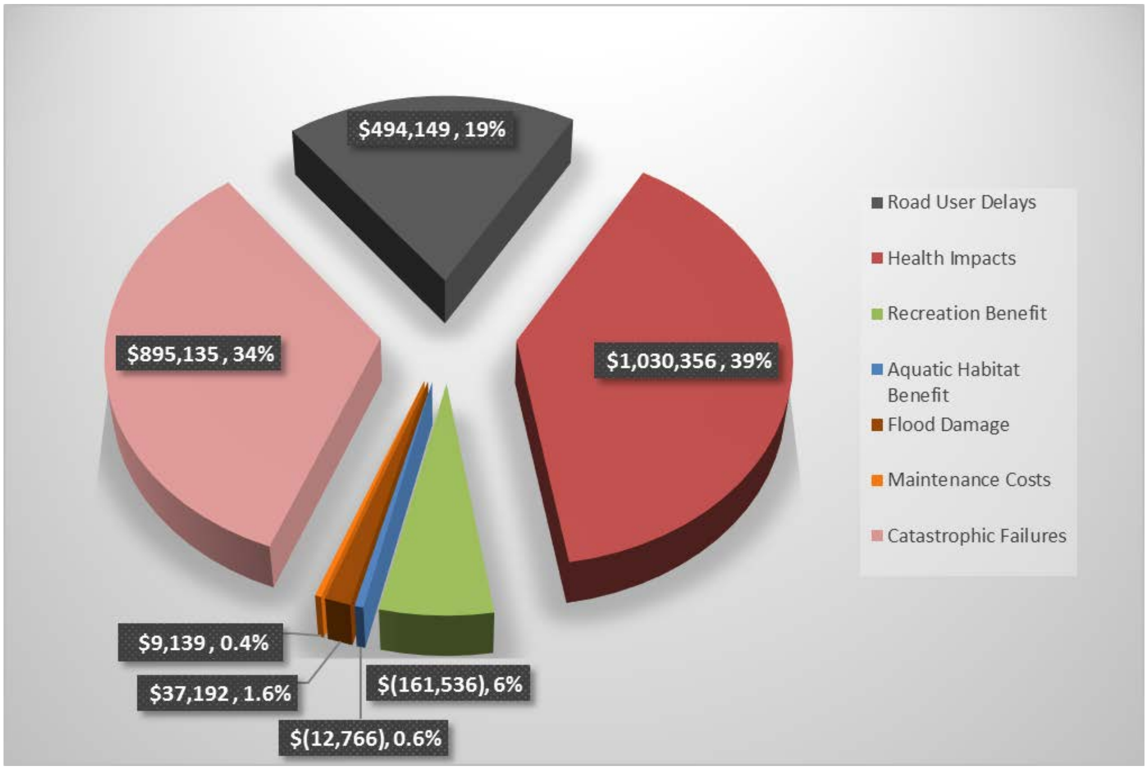
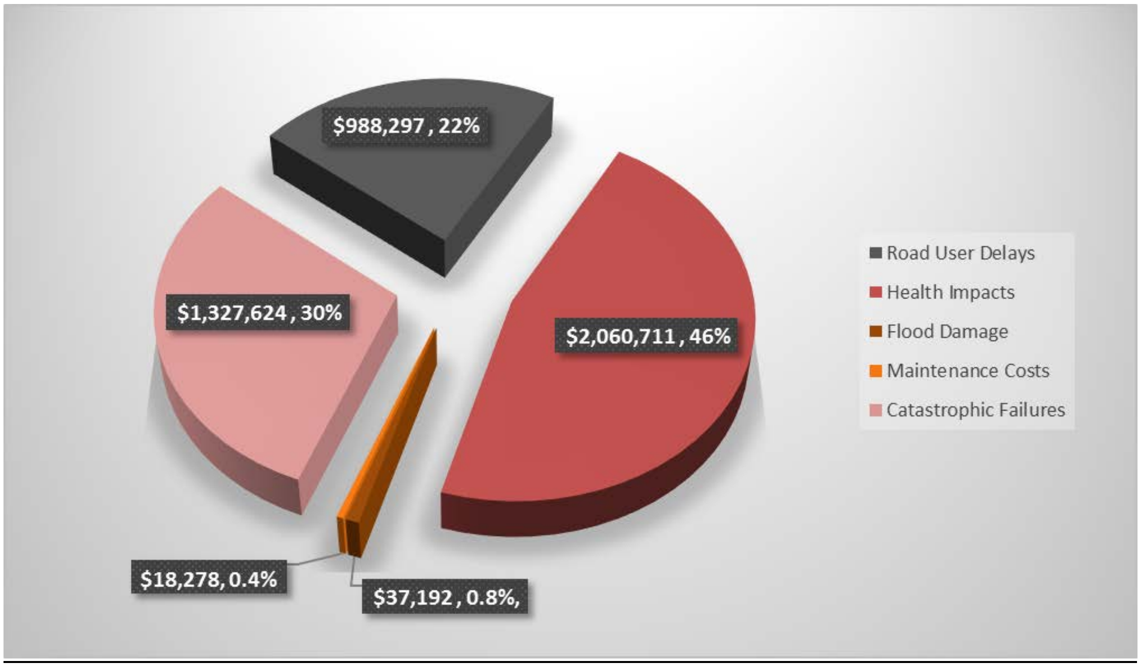


Figure 3h: Total accrued costs for a traditional design pipe culvert over a 50-year life span.

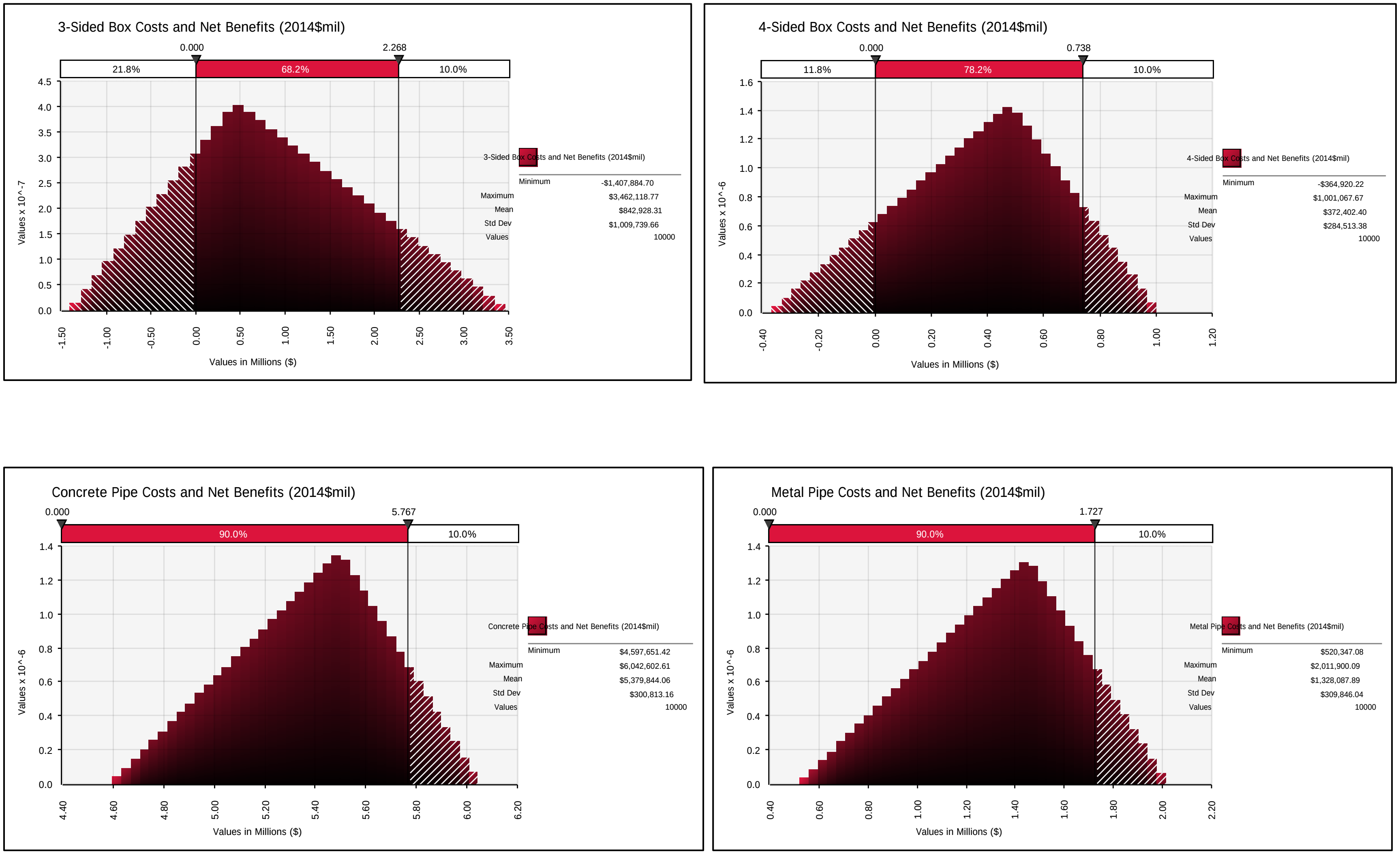


Monte Carlo Analysis

As part of the sensitivity analysis, a Monte Carlo Simulation was performed using the @Risk add-on to Microsoft Excel available from Palisade Software. Simulations on the costs were conducted and each simulation is composed of ten thousand iterations. This number of simulations is sufficient to promote stability and consistency in the output values should simulations be repeated with identical input values. In an iteration, the software randomly draws a single point estimate from input probability distributions for each budget line item, drawing from the median, low and high estimates according to the probabilities represented in the shape of the input distributions (e.g., values greater than the 90 percent confidence interval are selected only 10 percent of the time). Line items are then summed to estimate the total cost for each iteration. A probability distribution for the output measure (total accrued cost over 50-year period) is based on the totals calculated for each of the ten thousand iterations in a simulation.

The simulation was performed on the capital costs of the AOP design and their effect on the net benefits of each type of culvert. Figure 4 presents the graphs generated by the simulation. The graphs shows the percentage of the iterations that resulted on net benefits based on the range of capital costs of the AOP design culverts. For a 3-sided box culverts, approximately 80% of the simulations resulted in a net benefit (i.e., each data point to the right of the zero on the graph), while for 4-sided box culverts, the percentage grows to approximately 90%. For metal pipes this percentage grows to a nearly 100% of the iterations showing net benefits.

Figure 4: Monte-Carlo analysis results depicting the total accrued costs for an AOP design 3-sided box culvert over a 50-year life span.



6.0 Framework for DOTs and Other Agencies to Capture Project Costs over Time

Transportation agencies have developed and maintained various forms of bridge, culvert and pipe condition databases for several years as a means to better manage their assets (NCHRP, 2002). As the use of more structured asset management systems have been widely adopted by DOTs, the opportunity to integrate expanded inventories has been made possible. With the passage of the 2012 Moving Ahead for Progress in the 21rst Century Act (MAP-21), a requirement was set for state transportation agencies to adopt risk-based asset management plans with the purpose of more closely tracking and managing critical assets. The FHWA and U.S. Department of Transportation (USDOT) recently issued their Final Rule (Federal Register Vol. 81, No. 205, October 24, 2016) requiring the implementation of certain MAP-21 requirements that address state development and implementation of an asset management plans for DOT managed components of the National Highway System, including culverts and bridges. The asset management plan includes life-cycle planning for asset classes, and the identification of risks to assets such as extreme weather events. The plan also requires the inclusion of financial risks associated with budget uncertainty; operational risk from asset failure; and strategic risks associated with environmental compliance. The asset management systems could serve as an appropriate system for tracking stream crossing cost items and support the financial risk calculations.

Many DOTs have developed in-house databases or inventories of the type and condition of bridges and major culverts. The range of structure characteristics include coordinate location, roadway type, structure, age, span type, span size, construction materials, end protection, bank protection, inspection and condition assessment results for roadway and structure, overall condition rating, and channel condition and bankfull width, etc. A survey of 3 state DOTs and a County was conducted in 2013 by FHWA (2014) to provide insight into the culvert management programs used by these agencies to inventory and track culvert condition, extend culvert life, and reduce risk. Two of the key best practices noted in the report was improving awareness of culvert failure risks within regional districts and higher management to gain acceptance of the need to manage the risk through an inventory program, and the starting with a simple program with reduce data entries would gain quicker acceptance and use and could be built upon over time.

Existing culvert inventories and databases do not include cost information for original construction, replacement costs, or maintenance costs. Modifying these inventories may be the most effective means for DOTs to develop a broad set of data points within individual states to help track life cycle costs. To assist in the future analysis of life-cycle cost and benefit-cost analysis, the recommended data collection is listed in Table 8. The list could be amended to reflect regional issues should certain factors have a greater affect, such as material cost or wetland replacement. Ideally, the database would allow supporting electronic files (photos, documents, spreadsheets) to be appended to the entries.

Systematic data collection and transfer into a standardized asset management system is likely to produce a more reliable data set to support future analysis of benefits and costs and long-term trends. The records provided for this study were inconsistent in the level of detail, with some DOTs providing much more detailed data records than others. While this is understandable in that different DOTs have had different priorities and strategies to address their individual culvert replacement and maintenance issues, the lack of consistency restricts availability of suitable data to conduct more detailed analyses and trends. The use of consistent data collection and reporting methods within an asset management system will address the data quality issue.

Table 8: Example items to incorporate in a culvert management database.

Category		Information Type
Structure Characteristics		
	Crossing Name	Stream name
	Drainage Basin	HUC code
	Culvert Location	Coordinates
	Structure Type	
	Structure Size	Span Length, Width or Diameter
	No. of structures at crossing	
	Installation Date	Month/Year
	Condition Rating	DOT based rating method
Design Width		
AOP Approach	Stream Simulation	
AOP Approach	HEC-26/Bankfull * Safety Factor	
Non-AOP Approach	Traditional Hydraulic Capacity	
Cost Information		
	Design/Permitting Fees	Total cost / Date
	Engineers Estimate	Estimated Cost/ Date
	Construction Cost	Total Cost / Date
	ROW Acquisition	No. of Parcels, Acreage, Total Cost, Date
	Reconstruction Cost	Total cost / Date
	Maintenance/Repair Cost	Total cost / Date
Environmental		
	Aquatic Connectivity Rating	Rating Methodology Input
	Aquatic T&E Species Present	Listed species
	Aquatic Connectivity	Required – Yes/No
		Priority – Anticipated Date
		Restored / Date

A regional approach for stream crossing data collection and management with the goal of improving aquatic connectivity was prepared through a collaborative effort by a network of non-profit organizations and state and federal natural resource agencies. The North Atlantic Aquatic Connectivity Collaborative (NAACC) was established by the University of Massachusetts Amherst (UMassAmherst), US Fish and Wildlife Service, Gulf of Maine Coastal Program, Vermont Department of Fish and Wildlife, US Forest Service, and The Nature Conservancy to establish a program for the inventory and management of stream crossing data with a goal of improving aquatic connectivity across a thirteen-state region, from Maine to West Virginia (NAACC, 2014). Over the past several years NAACC has been building up the database of stream culverts and bridges using data collected by DOT staff and voluntary efforts in accordance with detailed culvert survey protocols. The database and related research has been supported by four transportation agencies and has been used to support prioritization and funding decisions for culvert and bridge upgrades and replacements. While this database is useful for the purpose of inventory, condition rating of aquatic connectivity, and prioritization of replacement projects, vital cost information on culvert and bridge replacements that could support future benefit-cost analysis is not included in the current database. Amending the database to include this information would require further collaboration with transportation agencies and NAACC.

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APPENDIX A – SUMMARY OF AQUIRED PROJECT DATA

	A	B	D	F	H	J	N	O	P	Q	S	T	U	AF	AG	AH	AI	AJ	AK	AO	AP	AQ	AR
2	**APPENDIX A: SUMMARY OF PROJECT DATA**										**AOP Design Method**												
3	**Tally**	**Crossing Name**	**Contact Agency**	**Region**	**Culvert Description**	**Number of Structures Associated with Crossing**	**Height of Span (ft)**	**Width of Span (ft.)**	**Length of Span (ft)**	**Length of Stream Channel Work**	**Stream Simulation**	**AOP/HEC-26 Hydraulic Design**	**Modified Hydraulic Design**	**Engineering & Design Cost 2**	**Permitting Cost**	**Construction Cost**	**Right-of-Way**	**Estimated Length (Ft) of Reconnected Stream Habitat**	**Estimated Acres of Reconnected Stream Habitat**	**Total Estimated Costs**	**Date of Cost Estimate**	**Cost with 2014 Inflation rate**	**Estimated Replacement In-kind Cost (2014)**
4	1	Hershey Run	Delaware DOT (DelDOT)	Northeast	4-sided box	1	4	10	44	NA			x	$235,461		$482,548	$22,393	1404	0.18	$750,258	2010	$817,781	$177,000
5	2	Gravelly Run	DelDOT	Northeast	3-sided box	1	6.5	22	30.5	40'			x	$4,099		$490,775	$1,554	9456	3.04	$466,105	2010	$508,054	$144,000
6	3	Hudson Branch (Fox Chase Road)	DelDOT	Northeast	3-sided box	1	6.5	20.5	36.5	NA			x	$6,509		$445,564	$2,287	7522	1.81	$386,701	2011	$406,036	$167,000
7	5	Savannah Ditch/Wharton Branch	DelDOT	Northeast	4-sided box	1	8	10	77.6	50'			x	$6,194		$525,142	$2,386	6105	1.82	$777,068	2013	$792,610	$104,000
8	8	Benton Hill Road	Massachsetts Dept. Ecological Restoration (MA DER)	Northeast	3-sided box	1	4	18	36					$22,758	$5,000	$158,044		553	0.15	$185,802	2009	$204,382	$56,000
9	10	Route 8 (Depot)	MA DER	Northeast	4-sided box	1	4	18	32					$24,742	$5,000	$171,819		1674	0.31	$201,560	2009	$221,716	$135,247
10	12	Rte 8 (Center Pond)	MA DER	Northeast	3-sided box	1	4	18	52					$16,719	$5,000	$208,981		940	0.46	$233,700	2009	$257,070	$156,813
11	15	Cross Place Culvert 2	MA DER, Foresight Land Services OPC	Northeast	4-sided box	1	4	4	34					$34,347	$9,000	$183,419		215	0.07	$217,766	2009	$239,543	$148,000
12	23	McNerney Road Bridge over Shaker Mill Brook	Massachusetts DOT (MassDOT)	Northeast	3-sided box	1	10	24	20.5	100			Combo stream simulation and hydraulic	$69,352				303	0.27	$961,233	2008	$1,057,356	$75,000
13	24	Route 2 over Oxbow Brook	MassDOT	Northeast	3-sided box	1	8.5	43	20	60			Combo stream simulation and hydraulic	$91,586		$1,611,412		2495	1.09	$1,702,998	2011	$1,788,148	$1,045,000
14	25	Route 2 over Wilder Brook	MassDOT	Northeast	3-sided box	1	6.5	43	24	60			Combo stream simulation and hydraulic					4357	2.35	$1,702,998	2011	$1,788,148	$1,018,000
15	26	Route 2 over Hartwell Brook	MassDOT	Northeast	3-sided arch	1	12	80	32	160			Combo stream simulation and hydraulic	$20,245		$1,410,660		2054	1.60	$1,430,905	2012	$1,473,832	$823,000
16	27	Bradford Brook	MaineDOT	Northeast	4-sided box	1	6	13	62	82'	x				$16,000	$754,000		1821	0.13	$962,000	2014	$962,000	$350,000
17	29	Andover Road Bridge over Meadow Brook	MaineDOT	Northeast	4-sided box	1	6	22	60	80'		X			$1,000	$324,819		1728	0.77	$469,569	2014	$469,569	$216,000
18	31	Aitkin	Minnesota DOT (MNDOT)	Midwest	4-sided box	1			16		MESBOAC				Not Considered	$35,429				$35,429	2009	$38,972	$35,763
19	32	Cottonwood (So. F Watonwan)	MNDOT	Midwest	4-sided box	2			14		MESBOAC				Not Considered	$74,754				$74,754	2009	$82,229	$78,975
20	33	Cottonwood (Unnamed)	MNDOT	Midwest	4-sided box	2			12		MESBOAC				Not Considered	$77,423				$77,423	2009	$85,165	$80,347
21	34	Fillmore, Donaldson Cr.	MNDOT	Midwest	4-sided box	3			16		MESBOAC				Not Considered	$188,604		10672	3.31	$188,604	2009	$207,464	$183,805
22	35	Fillmore, Duschee	MNDOT	Midwest	4-sided box	3			24		MESBOAC				Not Considered	$123,323				$123,323	2009	$135,656	$133,714
23	36	Fillmore, Money Cr.	MNDOT	Midwest	4-sided box	2			24		MESBOAC				Not Considered	$88,942				$88,942	2009	$97,837	$91,507
24	37	Jackson, Little Sioux	MNDOT	Midwest	4-sided box	3			24		MESBOAC				Not Considered	$77,894				$77,894	2009	$85,683	$89,992
25	38	Kandiyohi, CD27	MNDOT	Midwest	4-sided box	1			12		MESBOAC				Not Considered	$78,828				$78,828	2009	$86,711	$69,205
26	39	Meeker	MNDOT	Midwest	4-sided box	1			12		MESBOAC				Not Considered	$38,920				$38,920	2009	$42,812	$32,117
27	40	Mille Lacs, Mike Drew	MNDOT	Midwest	4-sided box	1			14		MESBOAC				Not Considered	$42,084				$42,085	2009	$46,293	$42,945
28	54	SR 9 - NP Creek	Wisconscin DOT (WSDOT)	Northwest	4-sided box	1	12	17	42	50'	x			$644,903		$539,724	$35,225	441	0.05	$1,219,852	2013	$1,244,249	$38,000

	A	B	D	F	H	J	N	O	P	Q	S	T	U	AF	AG	AH	AI	AJ	AK	AO	AP	AQ	AR
2	APPENDIX A: SUMMARY OF PROJECT DATA										AOP Design Method												
3	Tally	Crossing Name	Contact Agency	Region	Culvert Description	Number of Structures Associated with Crossing	Height of Span (ft)	Width of Span (ft.)	Length of Span (ft)	Length of Stream Channel Work	Stream Simulation	AOP/HEC-26 Hydraulic Design	Modified Hydraulic Design	Engineering & Design Cost 2	Permitting Cost	Construction Cost	Right-of-Way	Estimated Length (Ft) of Reconnected Stream Habitat	Estimated Acres of Reconnected Stream Habitat	Total Estimated Costs	Date of Cost Estimate	Cost with 2014 Inflation rate	Estimated Replacement In-kind Cost (2014)
29	55	SR 7 - Muck Creek	WSDOT	Northwest	3-sided box	1	10	23	87	95'	x			$476,904		$1,514,928	$2,638	664	0.21	$1,994,470	2013	$2,034,359	$80,000
30	56	SR 106 - Twanoh Falls Cr	WSDOT	Northwest	3-sided box	1	9	20	77	100'	x			$662,627		$1,988,473	$203,410	2074	0.31	$2,854,510	2013	$2,911,600	$10,000
31	57	SR 112 - Coville Cr	WSDOT	Northwest	3-sided box	1	9	24	99	120'	x			$485,160		$1,269,721	$0	2277	0.44	$1,754,881	2013	$1,789,979	$43,000
32	58	US 2 - Skinney Cr	WSDOT	Northwest	3-sided box	1	10	16	109	180'	x			$236,058		$704,538	$0	2323	0.40	$940,596	2013	$959,408	$55,833
33	59	SR 162 - Ball Cr	WSDOT	Northwest	4-sided box	1	5	12	48	78'	x			$361,359		$686,545	$24,893	8131	2.80	$1,072,797	2013	$1,094,253	$22,000
34	60	SR 21 - South Nanamkin Cr	WSDOT	Northwest	3-sided box	1	6	18	77	90'	x			$88,077		$754,515	$0	84480	50.42	$842,592	2013	$859,444	$41,000
35	64	Highland Road Creek/Highland Road (HRC PB 8)	Ozaukee, WI Planning and Parks Dept	Midwest	4-sided box	1	5	12	71			x	Fish X'ing	$2,400		$147,384		1852	0.47	$149,784	2012	$154,278	$212,000
36	65	Sandhill Creek SB 52	Ozaukee, WI Planning and Parks Dept	Midwest	4-sided box	1	4	12	24.75			x	Fish X'ing	$1,200		$44,896		891	0.18	$46,096	2012	$47,479	$188,000
37	4	Saulsbury Ditch	Delaware DOT (DelDOT)	Northeast	Concrete pipe	3	6	70	88	120'			x	$12,058		$246,767	$2,383	3754	1.25	$307,158	2014	$307,158	$326,000
38	6	Short & Hall Ditch	DelDOT	Northeast	Concrete pipe	3	6	64	88	60'			x	$3,509		$251,901	$5,089	5795	1.13	$249,799	2013	$254,795	$266,000
39	7	Bronson Brook Dingle Road Culvert	American Rivers, MA DER	Northeast	Metal arch	1	$9	$40	$20	$95		x	1.2X bankfull width per MA specs	122832		285027		896	0.246831956	407859	2006	477195.03	32000
40	9	Arthur Pease Road	MA DER	Northeast	Metal Pipe	1	5.6	14.8	30					$14,936	$5,000	$103,719		757	0.91	$123,654	2009	$136,019	$51,687
41	11	Route 8A (Drowned Land)	MA DER	Northeast	Metal Pipe	1	6	16	48					$43,941	$8,000	$457,719		1179	0.31	$509,660	2009	$560,626	$213,038
42	13	Stage Road Culvert	MA DER	Northeast	Metal arch	1	13.25	34.1	85					$35,000	included in Engineering	$305,000		659	0.19	$355,000	2012	$365,650	$135,000
43	14	Cross Place Culvert 1	MA DER	Northeast	Metal arch	1	10.1	29.1	22					$61,000	$9,000	$316,638		1637	0.32	$377,638	2013	$385,191	$172,000
44	16	Clark Wright Road 1	MA DER	Northeast	Metal arch	1	4.5	20.3	16					$61,000	$9,000	$114,618		666	0.15	$175,618	2013	$179,130	$68,070
45	17	Clark Wright Road 2	MA DER	Northeast	Metal pipe	1	6.2	14.4	20					$19,994	$9,000	$93,712		666	0.15	$113,706	2010	$123,940	$47,097
46	18	Cross Place Bridge 3	MA DER	Northeast	Metal arch	1	6	14.8	18					$61,000	$9,000	$121,474		1496	0.24	$182,474	2013	$186,123	$70,727
47	19	Bonny Rigg Hill	MA DER	Northeast	Metal arch	1	7	27	30					$40,000	$10,000	$470,150		962	0.20	$522,650	2013	$533,103	$16,000
48	20	Blair Road	MA DER	Northeast	Metal arch	1	5.4	25.6	63.25			Y		$77,200	$9,000	$313,624		1435	0.33	$390,824	2014	$390,824	$194,000
49	21	Goss Hill Road	MA DER	Northeast	Metal arch	1	4.2	19.1	54.25					$76,300	$9,000	$220,031		693	0.18	$296,331	2014	$296,331	$175,000
50	22	Route 112 (Kearney)	MA DER	Northeast	Metal arch	1	6.7	28.25	36.25					$71,200	$9,000	$539,138		1512	0.23	$610,338	2014	$610,338	$240,000
51	28	Route 131 Strut/ St. George	MaineDOT	Northeast	Concrete pipe	1	7	72	7	92'		x			$5,000	$178,793		105	0.02	$282,433	2014	$282,433	$220,000
52	30	Grover Brook	MaineDOT	Northeast	Concrete pipe	1	8	80	8	100'		x			$1,000	$174,335		721	0.28	$245,335	2014	$245,335	$144,000
53	41	Mille Lacs, Tibbets Brook	MNDOT	Midwest	Concrete pipe	1		10			MESBOAC				Not Considered	$22,370		8207	3.77	$22,370	2009	$24,607	$22,196
54	42	FR42.05.0 over Bingo Road	US Forest Service (USFS)	Northeast	Metal pipe	1	4.7	15	36	80'0"	x			$32,000	$0	$113,738	$0	3394	0.70	$145,738	2014	$145,738	$113,676
55	43	FR92.00.0 over Goshen Brook	USFS	Northeast	Metal pipe	1	6.3	20	46	154'0"	x			$31,023	$0	$119,835	$0	1031	0.50	$150,858	2014	$150,858	$132,755
56	44	FR92A.00.0 over Hale Brook	USFS	Northeast	Metal pipe	1	3.9	52	52	65'0"	x			$29,016		$113,725		1708	0.22	$142,741	2014	$142,741	$129,894
57	45	Road 6031 milepost 0.583	USFS	Northwest	Metal pipe	1		5			x							1804	0.17	$18,596	2006	$21,757	$21,970
58	46	Road 6031 milepost 6.166	USFS	Northwest	Metal pipe	1		6.5			x							1024	0.11	$25,484	2006	$29,816	$31,214
59	47	zarembo beach option 3/6585-5.285	USFS	Northwest	Metal pipe	1		11					x					4370	0.70	$52,816	2006	$61,795	$43,931
60	48	Road 6031 milepost 0.597	USFS	Northwest	Metal pipe	1		5					x					1804	0.17	$29,514	2006	$34,531	$30,779
61	49	Road 6031 milepost 3.833	USFS	Northwest	Metal pipe	1		5					x					1804	0.17	$24,766	2006	$28,976	$25,687

	A	B	D	F	H	J	N	O	P	Q	S	T	U	AF	AG	AH	AI	AJ	AK	AO	AP	AQ	AR
2	**APPENDIX A: SUMMARY OF PROJECT DATA**										**AOP Design Method**												
3	**Tally**	**Crossing Name**	**Contact Agency**	**Region**	**Culvert Description**	**Number of Structures Associated with Crossing**	**Height of Span (ft)**	**Width of Span (ft.)**	**Length of Span (ft)**	**Length of Stream Channel Work**	**Stream Simulation**	**AOP/HEC-26 Hydraulic Design**	**Modified Hydraulic Design**	**Engineering & Design Cost 2**	**Permitting Cost**	**Construction Cost**	**Right-of-Way**	**Estimated Length (Ft) of Reconnected Stream Habitat**	**Estimated Acres of Reconnected Stream Habitat**	**Total Estimated Costs**	**Date of Cost Estimate**	**Cost with 2014 Inflation rate**	**Estimated Replacement In-kind Cost (2014)**
62	50	Zarembo Interior Option 2/ 6585-7.968	USFS	Northwest	Metal pipe	1		20					x					6188	1.63	$141,565	2006	$165,630	$103,212
63	51	Fire Cove, 8060-2.305	USFS	Northwest	Metal pipe	1		5					x					387	0.04	$37,627	2006	$44,023	$30,908
64	52	Road 6031 milepost 3.161	USFS	Northwest	Metal pipe	1	6.6	9.75					x					1480	0.22	$40,557	2006	$47,451	$38,732
65	53	Road 6317 milepost 5.699	USFS	Northwest	Metal pipe	1		$6			x							689	0.079086318	25168	2006	29446.56	23538.06
66	61	Mole Creek/HWY O (MC PB 2)	Ozaukee, WI Planning and Parks Dept	Midwest	Metal arch	1	8.5	24.25	72	60'	x	x		$83,967		$496,164		3355	0.81	$580,131	2013	$591,734	$337,000
67	62	Riveredge Creek/HWY Y (REC PB 3)	Ozaukee, WI Planning and Parks Dept	Midwest	Aluminum 4-sided box	1	7.4	12	54			x	Fish X'ing	$3,000		$114,609		4389	1.21	$117,609	2010	$128,194	$230,000
68	63	Lac Du Cours Creek/River Road (LDC PB 1)	Ozaukee, WI Planning and Parks Dept	Midwest	Aluminum 3-sided box	1	4.8	10	27			x	Fish X'ing	$3,000		$62,306		1482	0.26	$65,306	2010	$71,184	$197,000