MassHighway Guidance Handbook: Design of Bridges and Culverts for Wildlife Passages

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Abstract

The Massachusetts Highway Department (MassHighway) has jurisdiction over numerous roadway stream crossings. Existing bridges and culverts, as well as future structures, could potentially affect aquatic and terrestrial wildlife movement along the streams and riparian corridors. MassHighway considers it important to design new and replacement stream crossings to accommodate wildlife passage and prevent adverse impacts to important ecological systems. Therefore, MassHighway is developing guidance for its planning and design staff and consultants to address wildlife passage issues at new and replacement bridges and culverts and to comply with regulatory standards for stream crossings.

The guidance handbook is a “work in progress” undergoing review and refinement in coordination with MassHighway staff and state and federal environmental resource agencies. The evolving guidance document addresses the following:

1. **Criteria for Wildlife Passage**: guidance on planning, selection, and design of new stream crossing structures and the reconstruction or replacement of existing bridges and culverts, with consideration of the needs for wildlife passage.

2. **Applicable Regulatory Standards**: an overview of the rationale for integrating wildlife passage elements into the design of bridges and culverts, and a description of the state and federal regulatory framework for developing stream crossing structures that provide habitat connectivity, based on guidance issued in the Massachusetts River and Stream Crossing Standards (2006).

3. **Design Approaches**: examination of an array of design approaches for conveyance of flows at stream crossings, while accommodating the passage of wildlife. The approaches include the entire range from full aquatic and terrestrial passage, to flood conveyance only, with an emphasis on accommodation to the maximum extent practicable within applicable project constraints. Referenced techniques include clear-span structures, “stream simulation” design, other embedded culvert designs, baffled culverts, and associated upstream and downstream ancillary measures to enhance wildlife movement. The document is not an exhaustive technical reference, but introduces suitable measures and provides citations to technical reference materials for detailed design procedures.

4. **Design and Implementation Constraints**: identification of common constraints that apply to the development of bridge and culvert designs, particularly at replacement crossings, to enable collection of pertinent information for choosing a structure that would maximize wildlife passage, while addressing other critical design parameters such as flood control, right-of-way limitations, structural integrity, other regulatory requirements, and construction feasibility.

5. **Development and Design Process**: explanation of how MassHighway integrates wildlife passage design into its process for project initiation, planning, development, and design.

Project planners and designers will use this guidance in conjunction other standard MassHighway technical references to evaluate, select, and design stream crossings for conveyance capacity, structural integrity, and wildlife habitat continuity.

Introduction

MassHighway transportation facilities, including existing and potential new roadways, involve numerous bridge and culvert crossings of streams and rivers. These crossing structures potentially affect the ability of both aquatic and terrestrial wildlife to move along the streambeds and riparian corridors, which in turn potentially affects the viability of wildlife populations and ecological systems. MassHighway is therefore developing guidance for its professional staff and consultants to comply with applicable regulatory standards and address wildlife passage issues at new and replacement bridges and culverts.
The guidance is founded upon the overall guiding principles provided by MassHighway’s *Project Development and Design Guide* (2006), which states:

> “The Commonwealth of Massachusetts is committed to caring for the built and natural environments by promoting sustainable development practices that minimize negative impacts on natural resources, historic, scenic and other community values, while also recognizing that transportation improvements have significant potential to contribute to local, regional, and statewide quality of life and economic development objectives…

> “…Well-designed transportation infrastructure that is responsive to its context is the product of thoughtful planning. By bringing together transportation professionals, local residents, and interest groups, transportation planning can produce public facilities and programs that support community goals, provide safe and efficient transportation for individuals and goods, enhance the economy, and protect the natural environment.”

In keeping with the overall direction established by the *Guidebook*, the guidance document addresses the following, as discussed further in the remainder of this paper:

2. Applicable Regulatory Standards.
3. Design Approaches for Wildlife Passage at Stream Crossings.

**Discussion**

**MassHighway Criteria for Wildlife Passage**

Where roads cross streams, the crossing can obstruct the movement of wildlife and result in the fragmentation of habitat. This loss of “habitat continuity” can result in significant impacts to wildlife, including both aquatic and terrestrial species.

From the roadway design perspective, crossings of streams using bridges or culverts must be designed for the roadway to have a width, slope, and surface treatment that provides for the free flow of traffic across the structure. Bridges and culvert crossings must be continuous in horizontal and vertical alignment with the approaching roadway, and accommodate the vehicle types, sizes, speeds, and traffic volumes using the approaching roadways. Crossings not meeting all these criteria would impede traffic movement.

From the habitat perspective, a bridge or culvert crossing must provide an opening that has a width, slope, and surface treatment that provides for the free conveyance of water, sediment, and debris - and in addition, both the upstream and downstream movement of aquatic and terrestrial organisms. For habitat continuity, a crossing must be continuous with the horizontal and vertical alignment of the upstream and downstream channel, convey the flow of sediment and debris as well as water, and accommodate the full range of wildlife types, life stages, movement abilities, and movement behaviors found in the nearby stream system. Crossings not meeting all these criteria would obstruct the passage of wildlife. The potential consequences of such obstructions include reduced access to vital habitats, such as spawning or seasonal feeding areas; population fragmentation and isolation, affecting genetic processes that maintain healthy regional populations; and loss of opportunity for populations to expand or re-establish themselves by colonizing otherwise viable locations in the stream system.

The roadway designer’s challenge is to provide bridges or culverts that do not result in obstructions, and thus maintain habitat continuity. Note that “habitat continuity” is not just a concern for anadromous fish, or even just for “fish,” but for a full range of aquatic and terrestrial species that depend on access to habitat within and along a stream.

The preservation and restoration of habitat continuity is particularly challenging at existing crossings, where past design decisions and historic land use impacts have resulted in barriers to wildlife movement. At these locations, site constraints often limit the choice of options for the replacement of bridge and culvert structures.

To promote a sound approach to the design of bridges and culverts that address wildlife passage, MassHighway is...
developing a guidance document that establishes criteria for the consideration of wildlife accommodation in the context of site constraints, when planning, selecting, and designing new and replacement stream crossing structures. MassHighway’s bridge and culvert installation, repair, and replacement activities fall into three major categories: maintenance repairs and bridge preservation, reconstruction of existing facilities, and new construction. For each of these broad categories of activities, there are differing opportunities and constraints for the provision of wildlife passage. MassHighway is considering the following basic criteria for each of these categories of activities:

**Maintenance Repairs and Bridge Preservation**

MassHighway maintains roadway infrastructure to provide for the continuing safety and serviceability of existing roadways. These activities sometimes require immediate repair or replacement of part or all of an existing culvert or bridge structure, to prevent a failure of the road surface, supporting structure, and embankment. Because of the immediacy of such repairs, there are only limited opportunities for modifications to address wildlife passage during these activities.

**Criteria:**

- Repair or replacement of each structure would be essentially “in-kind,” providing a design that maintains hydraulic capacity, does not significantly increase flow velocities or flood elevations, and provides for similar embedment as the replaced structure. The type of structure and its material may vary (for example, a collapsing corrugated metal pipe could be replaced by a concrete pipe), as long as these conditions are met.
- Such repairs and replacements would be limited to the damaged or deteriorated structure, and not extend into adjacent resource areas except as required to complete the required repair.
- The replacement structure invert may be modified to offset an existing drop (e.g., a “perched culvert” may be reconstructed with a lower invert), if the replacement structure is designed in such a way that it does not increase inlet or outlet velocities, does not increase scour at the inlet or the outlet of the structure; and does not expose the upstream channel to potential erosive scour, which could result in “head-cutting” of the upstream channel.
- At the time the repair is executed, MassHighway would note conditions at the crossing structure that may affect the accommodation of wildlife, so that future roadway and structure improvement projects address these conditions.

**Reconstruction**

Many MassHighway projects are planned and designed for the reconstruction and replacement of existing bridges and culverts at stream crossings to improve and upgrade existing roadways to meet evolving transportation needs and safety standards. These projects proceed under the Development and Design Process, as described in MassHighway’s *Project Development and Design Guide* (2006), which requires the consideration of environmental context in the selection and design of stream crossings. Design must address wildlife accommodation in conjunction with other project objectives. Generally replacement structures would consider wildlife accommodation to the extent practicable within project constraints, and with consideration of the type and significance of the habitat affected by the crossing.

**Criteria:**

- Bridges and culverts that currently do not comprise significant barriers to aquatic passage may be replaced in-kind or with an alternative structure with a comparable or greater span and waterway opening.
- Bridges and culverts that are currently significant barriers to aquatic passage would be evaluated to determine acceptable criteria for addressing the obstruction.
- If a design proposes the replacement of an existing a bridge span with a design requiring additional intermediate piers, a single span box culvert, or a multiple span box culvert, then MassHighway would evaluate the structure in coordination with the other affected natural resource agencies early in the development and design process, to determine acceptable criteria for the structure.
- Where prudent when considered in conjunction with project costs and other engineering design criteria applicable to the crossing, the bridge or culvert selection process would evaluate alternatives for enhanced wildlife accommodation, addressing terrestrial as well as aquatic species. This evaluation would consider site-specific stream and floodplain characteristics, habitat significance, and structural and economic feasibility.
Generally, evaluation of practicable alternatives for replacement of such structures would follow the order of preference in Table 1.

In considering wildlife accommodation for replacement structures, the designer must consider the applicable constraints, as described later in this paper.

<table>
<thead>
<tr>
<th>Order of Preference</th>
<th>Alternative Design Measure (see note)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Valley Span or Stream Span</td>
<td>At a minimum, strive for a clear span of stream, 1.2 times bankfull width; Valley Span may be considered where practicable.</td>
</tr>
<tr>
<td>2</td>
<td>Stream Simulation or No-Slope Culvert</td>
<td>Embedded culvert with “stream simulation” or “no slope” design, with span of 1.2 times bankfull width.</td>
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</tbody>
</table>
| 3                   | Integral Abutment Bridge Replacement, Full-Span Multiple Barrel Box Culvert, Roughened Channel Design, | Bridge span, open bottom culvert, or embedded culvert, less than 1.2 times bankfull width, with stable bed material design (e.g., “roughened channel design”) This also includes but is not limited to the following options:  
  - Integral abutment bridge replacements, with less than 1.2 times bankfull width between existing abutments.  
  - Multiple barrel culvert designs, even if combined width of all barrels exceeds 1.2 times bankfull width. |
| 4                   | Simple Embedded Culvert                                                                              | Generally should only be considered where bed material is self-sustaining, and does not warrant a “roughened channel design” to assure bed material stability.                                           |
| 5                   | Fish Passage Hydraulic Design                                                                        | Culvert or bridge with provisions for fish passage if applicable species are present.                                                                                                                |
| 6                   | Flow Conveyance Design                                                                              | All structures must address flow conveyance criteria under MassHighway and other regulatory standards. However, this alternative does not explicitly address wildlife passage accommodation, and is considered the minimum criteria for stream crossing design. |

Note: See discussion of alternative design measures under “Design Approaches.”

Table 1. Order of Preference for Alternative Design Measures for Maximizing Wildlife Passage

New Construction

MassHighway undertakes construction of new roadways to meet the transportation needs of the Commonwealth of Massachusetts. Where these projects require new stream crossings, the selection and design of structures will require integration of wildlife accommodation.

Criteria:

- The structure would be designed to meet guidelines for span width, open area and clearance, and stream bed composition set forth in “General Standards” in the Massachusetts River and Stream Crossing Standards (discussed further under “Applicable Regulatory Standards”). Bridge or spanning techniques are preferred, but pipe, box, and arch pipe culverts may be used where they can be designed to meet the specified dimensional, hydraulic, and streambed material requirements.
- Spanning or bridging techniques, including bridges, open bottom arches, and open bottom culverts, would be required for certain state-designated Outstanding Resource Waters.
In locations where state resource agencies have identified habitat of particular importance because of regional
habitat connectivity, the bridge selection process would evaluate alternatives that would meet certain
“Optimum Standards” offered by the Massachusetts River and Stream Crossing Standards. The evaluation
would consider these alternatives in light of site-specific stream and floodplain characteristics, habitat
significance, and structural and economic feasibility.

Where a bridge is proposed and the width of the crossing is such that a clear span is not structurally feasible
and a multiple span structure is necessary, MassHighway would engage in early coordination with natural
resource agencies to establish acceptable criteria for the placement of intermediate piers or other supporting
structures within the affected streambed or stream bank.

In designing for wildlife accommodation at new crossings, the designer must consider the applicable
constraints, as described later in this paper.

Applicable Regulatory Standards

The guidance will present an overview of the rationale for integrating wildlife passage elements into the design of
bridges and culverts, describe a method for assessing the degree of wildlife passage afforded by a structure,
summarize key elements of the Massachusetts River and Stream Crossing Standards, and describe the regulatory
framework for developing stream crossing structures that provide habitat connectivity.

Traditionally, bridges and culverts have been designed based on structural integrity and hydraulic capacity and
efficiency. We have learned over time that the hydraulic efficiency of these structures results in significant constraints
on passage of fish and other wildlife. For example, aquatic organisms must overcome a series of thresholds to pass
the full length of a “typical” culvert, including physical drops at the outlet and inlet of the structure; inadequate depths
of flow within the structure during base flow conditions; high flow velocities over relatively long distances; and
differences from natural conditions such as lighting, bottom composition, air movement, and other conditions that
impose behavioral deterrents to passage.

Natural streambeds offer multiple opportunities for movement in the water column at any given time, including diverse
velocity conditions and resting pools under a wide range of flow conditions; and opportunities for movement under
varying discharge events, including flood flows. Natural streams also offer opportunities for movement of aquatic
species on and within the stream bed as well as terrestrial passage along the stream banks.

Because of such conditions, natural stream beds provide a potential model for culvert and bridge design that would
accommodate wildlife. Crossing structures designed to span the existing stream bed, or replicate the natural stream
bed within the structure, and provide an opening capable of passing flood flows while maintaining stream bed stability,
offer the greatest potential for accommodating a wide range of wildlife at these crossings. The River and Stream
Continuity Partnership, which includes the University of Massachusetts Amherst, Massachusetts Department of Fish
and Game Riverways Program, and The Nature Conservancy, developed the Massachusetts River and Stream Crossing
Standards, to provide guidance in developing such stream crossings. This guidance document offers standards that
derive from a “Stream Simulation” design approach. Stream simulation addresses wildlife accommodation by providing
a continuous natural or “near-natural” stream bed and stream banks within the crossing, maintaining connectivity with
the existing stream system. The Massachusetts River and Stream Crossing Standards are not in themselves regulatory
(although state and federal permitting programs now reference the standards), but were developed to help guide
planning and design of structures for wildlife accommodation.

These standards generally provide for the following:

1. Bridge spans are preferred, but well designed culverts and open-bottom arches may be appropriate;

2. If culverts are used, then they should be embedded (varies with type of culvert);

3. Span the channel a minimum of 1.2 times the bankfull width;

4. Provide natural bottom substrate (streambed material) within the structure;

5. Design the bottom substrate with appropriate bed forms and streambed characteristics so that water depths
   and velocities are comparable to the natural channel for a variety of flows; and

6. Provide an “openness ratio” (area of opening divided by length of conduit) that fosters wildlife use of the
   structure. This ratio varies from 0.25 meters to 0.75 meters, depending on the significance of the stream to
   regional habitat connectivity, and the characteristics of the transportation crossing.
MassHighway’s criteria for crossing structures (discussed in the previous section of this paper) are being developed to address these recommended standards to the extent practicable.

The Regulatory Framework

Federal and state regulatory and wildlife agencies seek designs that preserve and restore habitat continuity. Knowing that natural stream features provide this continuity, this regulatory interest has led to permit programs that reference the Massachusetts River and Stream Crossing Standards to promote crossing design techniques that foster the preservation or replication of natural stream features at culverts and bridges. The permit programs essentially require new crossings to comply with this guidance. Regulatory programs also strive to implement the guidance at projects involving replacement or reconstruction of culverts and bridges on streams throughout the state. The Stream Crossing Standards contain specific recommendations for replacement of existing structures, acknowledging the limits imposed by site constraints at existing crossings.

The primary regulatory framework for Massachusetts highway projects consists of federal review under the jurisdiction of the U.S. Army Corps of Engineers (USACE), and state review under the Massachusetts 401 Water Quality Certification process.

The New England District of the U.S. Army Corps of Engineers (USACE) issued a Programmatic General Permit (PGP) for the Commonwealth of Massachusetts in January 2005, and modified the permit in December 2006. The PGP expedites review of activities that would have minimal impact in coastal and inland waters and wetlands in Massachusetts. The PGP covers activities in resource areas regulated by the USACE under Section 10 of the Rivers and Harbors Act of 1899, Section 404 of the Clean Water Act (CWA), and Section 103 of the Marine Protection, Research and Sanctuaries Act. The PGP establishes conditions for Category 1 (non-reporting) and Category 2 (reporting-requiring screening) activities.

The PGP requirements for all temporary and permanent crossings to have crossing structures designed to withstand and prevent the restriction of high flows, and so as not to obstruct the movement of aquatic life indigenous to the waterbody beyond the actual duration of construction. The PGP also requires new permanent crossings to conform to the General Standards contained in the Massachusetts River and Stream Crossing Standards.

The Massachusetts DEP 401 Water Quality Certification regulations are found in 314 CMR 9.00: 401 Water Quality Certification for Discharge of Dredged or Fill Material, Dredging, and Dredged Material Disposal in Waters of the United States Within the Commonwealth. This regulation governs the placement of fill in wetlands and waterways, in addition to regulating dredging activity and the handling of dredged materials. Under 314 CMR 9.00, certain projects do not require filing of a separate 401 Certification application, provided the projects meet specified conditions, including conformance to the requirements of the USACE PGP.

314 CMR 9.04 requires a 401 Water Quality Certification Application for certain types of projects, including activities that result in dredging or filling in any Outstanding Resource Water (ORW), or activities involving greater than 5,000 square feet of cumulative loss of bordering and isolated vegetated wetlands and land under water. For public roadway projects subject to this 401 Water Quality Certification review and involving a crossing of an ORW, a span or other bridging technique is required unless an alternative has been documented and approved under the application process.

MassHighway anticipates that new crossings – that is, roads built across streams where there currently exists no structure – will be designed to meet the Stream Crossing Standards, consistent with both the regulations and with MassHighway’s road and bridge design practices. For existing crossings, a balanced approach will be needed, so that the requirements of the Stream Crossing Standards are considered in light of site constraints on a project by project basis.

MassHighway’s Project Development & Design Guide, together with the Bridge Design Manual, provides direction to the design of projects that involve bridges and culverts. Both of these existing guides require early consideration of environmental conditions – including wildlife passage. They also call for early coordination with affected resource agencies, so that particular environmental issues are identified and addressed during the development and design process.

Design Approaches

The MassHighway guidance considers an array of design approaches for conveyance of flows at stream crossings, while accommodating the passage of wildlife. The approaches range from full aquatic/terrestrial passage, to general aquatic passage, to passage of specific aquatic species and life stages, to flood conveyance only. Referenced techniques
include clear-span structures, “stream simulation” design, other embedded culvert designs, baffled culverts, and associated upstream and downstream ancillary measures to enhance wildlife movement. The document will not be an exhaustive technical reference, but will introduce suitable measures and provide citations to technical reference materials for detailed design procedures (e.g., stream simulation design as described in the USDA Forest Service manual: *Stream Simulation: An Ecological Approach to Providing Passage of Aquatic Organisms at Road-Stream Crossings*).

Table 2 presents a list of general design approaches available for stream crossings to achieve varying degrees of stream continuity, ranging from “valley process” design to flood capacity design. A brief description of each of the design approaches follows. Figures 1.a. and 1.b. compare these approaches with the degree to which each is likely to address the provisions of the *Massachusetts River and Stream Crossing Standards*.

<table>
<thead>
<tr>
<th>Type</th>
<th>Provides Opening ≥ 1.2 x Bankfull Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Valley Span</td>
<td>Yes</td>
</tr>
<tr>
<td>2. Stream Span</td>
<td>Yes</td>
</tr>
<tr>
<td>3. Stream Simulation</td>
<td>Yes</td>
</tr>
<tr>
<td>4. No Slope Culvert</td>
<td>Yes</td>
</tr>
<tr>
<td>5. Integral Abutment Bridge Replacement</td>
<td>No (see Note 1)</td>
</tr>
<tr>
<td>6. Full Span Embedded Multiple-Box Culvert</td>
<td>Yes (see Note 2)</td>
</tr>
<tr>
<td>7. Roughened Channel Embedded Culvert</td>
<td>No</td>
</tr>
<tr>
<td>8. Simple Embedded Culvert</td>
<td>No</td>
</tr>
<tr>
<td>9. Fish Passage Hydraulic Design</td>
<td>No</td>
</tr>
<tr>
<td>10. Flow Conveyance Design</td>
<td>No</td>
</tr>
</tbody>
</table>

Note 1: Full span integral abutment replacement is considered a “stream span” design.

Note 2: Combined width of openings ≥ 1.2 x bankfull width.

**Table 2. Stream Crossing Design Approaches**

Note that the Valley Span, Stream Span, Stream Simulation, and No-Slope Culvert techniques (measures 1 through 4 in Table 2) would likely fully meet the *Stream Crossing Standards*, if appropriate openness ratios are provided. Because each river or stream crossing is unique, and because there are often significant constraints for replacement crossings, there will likely be conditions where replacement structures cannot be designed according to the techniques described for measures 1 through 4. In such cases, alternative measures will need to be considered to optimize the provision of passage for wildlife within applicable design constraints. Therefore, the other design approaches presented as measures 5 through 10 are described, to help aid in selection of an approach that can address the Standards to the maximum extent practicable.

1. **Valley Span**

   “Valley Span” crossing design involves the construction of a new bridge that completely spans the active floodplain of an existing stream, without disturbance of the streambed or its banks. This type of design allows for essentially unimpeded natural geologic, hydraulic, and ecological function of the stream and its floodplain. With specified clearances for wildlife passage, it would fully meet the *Stream Crossing Standards*, and would likely accommodate the movement of a full range of wildlife, including large mammals. This type of span might have intermediate structural supports founded within the floodplain. This design approach is not likely to be used for a replacement crossing, unless the existing crossing is itself a valley-span structure.

2. **Stream Span**

   Stream Span crossing design involves the construction of a new bridge, bottomless arch, or three-sided culvert over an existing stream without disturbance of the stream channel or its banks. A Stream Span crossing can also be provided for a replacement structure, where the existing structure spans the stream channel.
case of replacement structures, some stabilization or restoration of the existing stream or river may be required. If extensive work within the stream channel is necessary, then the design should be performed according to the “Stream Simulation” design approach discussed in this guidance document.

3. Stream Simulation

Stream Simulation design comprises a technique in which the culvert or bridge crossing is constructed with an integral, naturalized stream channel within the structure. The approach is intended to mimic the natural stream processes within the structure. The culvert or bridge opening is sized to meet or exceed the width specified in the Stream Crossing Standards. A streambed is constructed within the structure based on a geomorphologic evaluation of the existing streambed near or at the crossing, or a comparable “reference stream.” A “reference stream” consists of a stream reach with a drainage area, slope, and morphology similar to the proposed section of constructed streambed.

A culvert or bridge that is designed by the Stream Simulation technique maintains continuity of natural stream processes, including sediment transport, flood debris passage, fish passage, and the movement of other aquatic wildlife. The Forest Service Stream Simulation Working Group (2008) describes this design method in detail.

4. No-Slope Culvert

The “No-Slope Culvert” design is a special type of embedded culvert, with features intended to comply with the Stream Crossing Standards. A No-Slope Culvert consists of a typical box, arch, or pipe culvert installed with an invert slope of zero percent, embedded to a specified depth designed to retain a dynamically stable streambed within the structure. Under the MassHighway criteria, the No-Slope design would require the culvert width to equal or exceed 1.2 times the bankfull channel width, and the flow area to comply with the openness ratio specified by the Standards. Where a clear-span bridge or bottomless culvert design cannot be used, a No-Slope Culvert may be a reasonable option. Bates (2003) describes the design of this type of structure.

5. Integral Abutment Bridge Replacement

Integral Abutment Bridge Replacement (Figure 2) involves the construction of a new bridge structure founded on new abutments installed on the upland side of the existing bridge abutments. The existing abutments serve as coffer dams during construction. These abutments are kept in place permanently, but the tops of them are removed to provide clearance for the new bridge structural elements. Sometimes these old abutments are kept as short retaining walls; in other instances, they are cut off below the elevation of the stream bed. Generally, this design approach allows the bridge replacement to be conducted without performing work within the active stream channel, except when the old abutments are cut off below stream bed elevation.
Figure 1.a. Range of Stream Crossing Design Approaches (Adapted from Forest Service Stream-Simulation Working Group, 2008).
Figure 1.b. Range of Stream Crossing Design Approaches (continued),
(Adapted from Forest Service Stream-Simulation Working Group, 2008).
6. Full Span Embedded Multiple-Box Culvert

The Full Span Embedded Multiple-Box Culvert consists of two or more box culverts installed with an overall width equal to or exceeding 1.2 times the bankfull width of the stream. The inverts of the culverts are countersunk below the channel invert, allowing for the placement or natural accumulation of streambed material within the culvert. At least one of the culverts is designed to provide the openness requirement specified by the Massachusetts Stream Crossing Standards. Depending on the nature of the stream bed material, this type of culvert may require design similar to the “No-Slope” design with the invert of the culvert allowed to fill naturally, as a result of bed load movement through the structure. This process is referred to as “substrate recruitment”. In other cases, a stable substrate may need to be installed, following a design procedure similar to that required for the “Roughened Channel” design discussed below.

7. Roughened Channel Embedded Culvert

The Roughened Channel Embedded Culvert is one that may have a lesser width than specified by the Stream Crossing Standards, but has an engineered bed material designed to resist displacement from the culvert, prevent “subsurface flow,” and in some cases provide hydraulic conditions suitable for passage of specific fish species. Subsurface flow is a condition where flow through the culvert during low flow periods occurs within the void spaces in the substrate, as might occur through coarse material such as riprap. The Roughened
Channel Design procedure involves the sizing and gradation of material to sustain surface flow through the culvert, while meeting stability requirements. This design procedure is described by Bates (2003).

8. Simple Embedded Culvert

The Simple Embedded Culvert is a typical box, arch, or pipe culvert installed to maintain the slope of bed material in the culvert equal to that of the natural streambed. The culvert invert is countersunk below the channel invert and the culvert is usually filled with substrate graded to maintain surface flow and provide a stable bed form. The hydraulic capacity of the embedded culvert is evaluated based on the available flow area (deducting the embedded portion of the culvert from the cross sectional area of the culvert), with roughness based on the substrate material.

In some cases, embedded culverts can be installed with the invert depressed below the adjacent streambed, but without placement of substrate within the structure at the time of installation. Instead, the invert of the culvert is allowed to fill naturally, through “substrate recruitment”.

Unlike some of the other embedded culvert designs described above, Simple Embedded Culverts may not avoid or mitigate over the long term conditions such as hydraulic drops associated with the flow transition into the culvert under “inlet control” conditions, physical drops at the inlet and outlet, flow contraction at the inlet, scour pool formation at the outlet, or channel degradation downstream of the outlet. Also, the substrate may be subject to movement under flow conditions where the adjacent stream channel is stable. Because of the constricted flow area, higher velocities in the culvert may displace the bed material from within the culvert.

Culverts designed according to the “No-Slope Culvert” and “Stream Simulation” design approaches are special cases of “embedded culverts” but are addressed separately because of their ability to accommodate the full width and stream substrate conditions specified by the Stream Crossing Standards.

9. Fish Passage Hydraulic Design

This type of design involves the engineering of culverts and, in some cases, bridges to provide for the passage of specific species of fish, usually at specific life stages within those target species. This design approach applies measures to control heights of vertical transitions, flow velocities, and flow depths to within ranges that can be negotiated by the specific fish species. An example is the design of a structure to accommodate river herring, smelt, or salmon during seasonal spawning migration periods.

This method can be of limited value for general stream continuity, as it generally provides for passage for a narrow range of species, and within species a narrow range of swimming/jumping abilities. Examples of structures that provide for hydraulic conditions suitable for fish passage include:

- Low gradient culverts, designed for suitable flow depths and velocities for fish passage during low flows and flows associated with migration periods;
- Culverts with baffles, designed to introduce roughness or to alter flow regime within the culvert, thus controlling velocities and depths to specified ranges;
- Some embedded culverts (e.g., using “roughened channel design”), engineered to control depths and velocities of flow; and
- Bridges or large culverts that are retrofitted with fishways (e.g., “fish ladders”).

10. Flow Conveyance Design

This is the conventional approach for designing hydraulically and structurally efficient bridges and culverts. MassHighway guidance documents describe the hydraulic and structural design criteria in detail. Flow Conveyance Design is based on the capacity to carry specified design flows, consistent with the provision of a structurally sound structure that supports the required roadway. This approach also provides for adequate scour protection, flow transition at the inlet and outlet, and energy dissipation at the outlet. However, when bridges and culverts are designed solely for efficient flow conveyance, there are a number of features that can adversely affect aquatic and terrestrial wildlife passage. Structures must meet MassHighway flow conveyance criteria at a minimum, but in many cases other measures identified above are more likely to address the accommodation of wildlife.
Design and Implementation Constraints

The designer must address multiple design standards and regulatory criteria when designing a roadway stream crossing. The designer must also consider these criteria within the various constraints on the roadway and crossing structure design. The MassHighway guidance document will identify key constraints that may affect the selection and implementation of a design strategy for a stream crossing that accommodates wildlife. Definition of the constraints will enable collection of pertinent information for choosing a structure that would maximize wildlife passage, while addressing other critical design parameters such as flood control (for example, see Figure 4), right-of-way limitations, structural integrity, other regulatory requirements, and construction feasibility.

The proposed guidance document will describe common conditions that affect the design of road/stream crossings, particularly where the crossing already exists and must be considered in the context of existing land uses, utilities, flood plain elevations, and protected resource areas such as wetlands proximate to the crossing.

![Figure 4. Potential Alteration of Flood Elevations as a Result Culvert Replacement.](image)

Replacing an existing culvert with a culvert or bridge having a greater width and open area to meet wildlife accommodation objectives may result in sufficient increase in flood conveyance capacity to increase the downstream flood profile. This potential constraint must be considered in the design of replacement structures.

In addressing wildlife accommodation at new crossings and for replacement of existing bridges or culverts, the designer must consider the applicable constraints, including but not limited to those identified in Table 3. If any of these constraints affect the practicability of meeting wildlife accommodation objectives, then the designer would consult with MassHighway environmental staff and affected environmental resource agencies to establish acceptable criteria for the crossing.

Development and Design Process

The MassHighway handbook for Design of Bridges and Culverts for Wildlife Passage will not be a stand-alone document. The design of stream crossings with adequate flow capacity, structural integrity, and wildlife habitat continuity will require the designer to use this guidance in conjunction with other MassHighway reference manuals as well as other technical references specific to the design of the various alternative techniques presented in the discussion of “Design Approaches.”

MassHighway design guidance and practices include provisions to ensure that the project initiation, planning, development, and design process considers habitat continuity at stream crossings, provides for coordination with affected environmental agencies, and incorporates crossing design measures to achieve compliance with applicable
MassHighway projects advance from the identification of need to the construction of new and reconstructed roads and bridges in accordance with the Massachusetts Highway Development and Design Guide (2006). In addition, MassHighway’s Bridge Design Manual also governs the design of bridges as well as many culverts. The design of stream crossing structures must proceed in accordance with these fundamental MassHighway guidance documents and related MassHighway practices.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>CONSTRAINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural/Social</td>
<td>Site of crossing contains archaeological resources.</td>
</tr>
<tr>
<td></td>
<td>Crossing is a historic structure.</td>
</tr>
<tr>
<td></td>
<td>Adjacent historic structures may be affected by modifications to the crossing.</td>
</tr>
<tr>
<td></td>
<td>Stream crossing must be navigable by recreational and/or commercial watercraft.</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Approaching road grades are constrained by existing land use.</td>
</tr>
<tr>
<td></td>
<td>Available width of replacement structure is limited by minimum clearance to nearby buildings or other structures.</td>
</tr>
<tr>
<td></td>
<td>Utilities are located above, below, or on the existing crossing structure.</td>
</tr>
<tr>
<td></td>
<td>Utilities are located adjacent to the watercourse and may be affected by the crossing.</td>
</tr>
<tr>
<td>Structural</td>
<td>Lengths of bridge spans are limited by structural engineering requirements, as specified in the Bridge Manual.</td>
</tr>
<tr>
<td></td>
<td>Sizes of bridge components, manufactured arches, and culverts are limited to sizes that can be shipped overland to the construction site.</td>
</tr>
<tr>
<td></td>
<td>&quot;Aspect ratios&quot; of manufactured arches are constrained by structural requirements, limiting available options within vertical alignment constraints.</td>
</tr>
<tr>
<td></td>
<td>Feasibility of bridge construction may be affected by potential for scour.</td>
</tr>
<tr>
<td>Hydrologic/Hydraulic</td>
<td>Natural channel dynamics could result in potential channel adjustment (both vertical and lateral).</td>
</tr>
<tr>
<td></td>
<td>If existing structure provides flood flow attenuation, modification could affect downstream flood profile. This could require detailed flood study, preparation of LOMR under FEMA, and negotiations with downstream property owners.</td>
</tr>
<tr>
<td></td>
<td>Modification of crossing may result in potential for head-cutting of streambed upstream and/or sediment deposition downstream.</td>
</tr>
<tr>
<td></td>
<td>Modification of structure or adjacent channel may alter channel velocities or turbulence patterns.</td>
</tr>
<tr>
<td></td>
<td>Potential for scour at the structure may affect the choice of structure and foundation design.</td>
</tr>
<tr>
<td></td>
<td>Potential for scour at the outlet of the structure may affect the choice of structure design.</td>
</tr>
<tr>
<td></td>
<td>If downstream channel has undergone degradation, this may affect vertical alignment and choice of in-channel modifications, to achieve an effective passable crossing design.</td>
</tr>
<tr>
<td></td>
<td>Existing urbanization of the upstream and downstream channel may make it difficult or impossible to develop a &quot;natural&quot; crossing design. (Bankfull width may be indeterminate.)</td>
</tr>
<tr>
<td></td>
<td>On a coastal stream, an existing culvert may provide flood protection to inland areas, because its hydraulic capacity may prevent inundation by tidal floods.</td>
</tr>
</tbody>
</table>
### Table 3: Potential Constraints Affecting Design of Stream Crossings for Wildlife Accommodation

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>CONSTRAINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological/Ecological</td>
<td>Roadway impounded wetlands may have formed as a result of the existing structure alignment and hydraulics.</td>
</tr>
<tr>
<td></td>
<td>Protected resource areas at the toe of the existing embankment may constrain choice of structure and its horizontal and vertical alignment.</td>
</tr>
<tr>
<td></td>
<td>Upstream and downstream conditions may have highly favorable habitat conditions, and the new or replacement structure may be critical to habitat linkage (design of the local crossing must be considered in context of the stream system).</td>
</tr>
<tr>
<td></td>
<td>Upstream and downstream conditions may severely impede development of stream continuity (design of the local crossing must be considered in context of the stream system).</td>
</tr>
<tr>
<td></td>
<td>The construction process itself can have an adverse impact, depending on type of structure.</td>
</tr>
<tr>
<td></td>
<td>In some unique situations, the existing structure may provide a desirable obstacle to the passage of undesirable species.</td>
</tr>
<tr>
<td>Economic</td>
<td>Design costs of some structural systems may be prohibitive, depending on scale of project.</td>
</tr>
<tr>
<td></td>
<td>Construction costs of some structural systems may be prohibitive, depending on scale of project.</td>
</tr>
<tr>
<td></td>
<td>Costs to maintain some alternative crossing types may not be sustainable by the party responsible for long-term maintenance.</td>
</tr>
<tr>
<td></td>
<td>Additional right-of-way or easements may be required if work extends outside the right-of-way (e.g., upstream or downstream channel restoration required to accommodate crossing design).</td>
</tr>
<tr>
<td>Constructability</td>
<td>Choice of structure type may be affected by accessibility of work site.</td>
</tr>
<tr>
<td></td>
<td>Choice of structure type may be affected by a need to maintain traffic during construction.</td>
</tr>
<tr>
<td></td>
<td>Choice of structure type may be affected by feasibility of conducting construction operations within the limits of the stream or by other construction phase water handling requirements.</td>
</tr>
<tr>
<td></td>
<td>Choice of structure type may be affected permit time restrictions (“work in water” seasonal time limits).</td>
</tr>
<tr>
<td></td>
<td>Choice of structure type may be affected by feasibility of performing construction required construction operations (e.g., placement of materials within a culvert or beneath a bridge span) or other factors.</td>
</tr>
<tr>
<td>Maintainability</td>
<td>Choice of structure type may be affected by accessibility for required maintenance.</td>
</tr>
<tr>
<td></td>
<td>Choice of structure type may be affected by other maintenance considerations.</td>
</tr>
</tbody>
</table>

MassHighway’s Project Development and Design Guide sets forth specific requirements focused on the design of projects to address environmental context and to comply with regulatory programs. Pertinent sections of that guidance specifically apply to the design of new and replacement stream crossings. The design of stream crossings to address wildlife passage parameters and constraints is consistent with and required by the Design Guide.

The MassHighway Bridge Manual includes provisions that require the consideration of environmental context and pertinent design requirements in the development of bridge designs. The proposed new guidance would provide that the bridge type selection process consider wildlife accommodation at stream crossings, by considering streams and
rivers “environmentally sensitive areas” and addressing aquatic and other wildlife passage issues early in the evaluation of alternative structures for both new and replacement crossings.

The design of stream crossings to accommodate wildlife requires that the criteria for such passage be integral to the entire design process. The design cannot successfully implement stream continuity by introducing accommodation considerations near the end of the design process as an “add-on” feature. If a project will be required to meet the width, opening, and embedment requirements of the River and Stream Crossing Standards, the original analysis of the crossing and the structure selection process should address these criteria.

The integration of stream habitat continuity into all phases of crossing structure analysis and design development is essential to the successful implementation of stream crossings that functionally accommodate wildlife movement.

**Biographical Sketches**

David Nyman is Chief Engineer at Comprehensive Environmental Incorporated (CEI), with over 38 years of civil engineering experience. A leader in the storm water management field, Mr. Nyman’s consulting experience focuses on stormwater management and water resource protection and restoration issues for municipal and state projects, as well as private clients. Mr. Nyman has contributed as key author and project manager to the development of MassHighway’s Storm Water Handbook, New Hampshire Department of Environmental Service’s Statewide Stormwater BMP Manual, and the Massachusetts DEP’s Hydrology Handbook for Conservation Commissioners. He has participated river and stream habitat restoration projects, including culverts designed for wildlife accommodation, in Massachusetts, Connecticut, and Pennsylvania. He currently advises MassHighway on stream crossing design for habitat continuity, as well as on storm water management permitting and design issues. He is the primary author of the pending MassHighway Guidance Handbook: Design of Bridges and Culverts for Wildlife Passage.

Henry Barbaro, since 1993, has served as the Supervisor of the Wetlands & Water Resources Unit within MassHighway’s Environmental Services Division. During that time, he has worked on developing environmental management and compliance policies for MassHighway, including those for storm water management, standards for drainage tie-ins, and mitigation practices for snow and ice control. In addition, he is working with the U.S. Geological Survey to calibrate a highway contaminant loading model for TMDL compliance. Mr. Barbaro’s involvement with the stream crossing guidelines, described herein, is to develop cost-effective measures for enhancing aquatic ecosystems, and engage MassHighway’s design community in the application of these measures in coordination with state and federal regulatory programs.

**References**


