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State of the Practice for Managing, Maintaining and Operating Culverts: A Review of Deterioration Curves and Tools

The purpose of this TRS is to serve as a synthesis of pertinent completed research to be used for further study and evaluation by MnDOT. This TRS does not represent the conclusions of either CTC & Associates or MnDOT.

Introduction

When estimating the service lives of culverts, MnDOT generally relies on predictions of the durability of the pipe materials with which they are constructed. However, because of varying environmental conditions and other factors, this method is not always accurate. MnDOT is looking for other factors that affect the service lives of culverts under 10 feet in diameter and how these factors can be incorporated into mathematical models of culvert deterioration. MnDOT would also like to better quantify the effects of repairs.

To gather information for this effort, CTC & Associates:

- Conducted interviews with representatives from seven departments of transportation: Delaware, Florida, Michigan, Ohio, South Carolina, Virginia and Washington.
- Conducted a literature review on the state of the practice for managing, maintaining and operating culverts, in particular the effects of maintenance activities on culvert deterioration.

MnDOT is especially interested in information about models, tools and management systems; previously conducted research; and the state of the practice for culverts (under 10 feet in diameter) at other state DOTs and other transportation asset owners and managers. The literature review focused on finding research that can help answer the following questions:

1. What are the best practices for quantifying the benefits of culvert maintenance?
2. What deterioration models and/or curves exist for culverts (by construction material and design type)?

3. Do models incorporate culvert maintenance?
4. If models do not exist, are there other means by which states quantify treatment benefits?
5. How do maintenance treatments impact culvert life cycle or remaining service life?
6. What research is underway, has been completed or is needed on culvert deterioration (by construction material and maintenance schedules)?
7. How are other agencies defining culvert failure?

Summary of Findings

Survey of State Practice

CTC conducted interviews with representatives from seven DOTs: Delaware, Florida, Michigan, Ohio, South Carolina, Virginia and Washington. Interviewees were asked about the existence of deterioration models, their incorporation of the effects of culvert maintenance, life-cycle cost assumptions, the definition of culvert failure and their awareness of related research. Highlights include:

- **Deterioration models:** Only Delaware and Virginia use deterioration models for culverts, and Virginia uses them only for culverts greater than 10 feet in diameter. Both states use Pontis. Florida is engaged in an ongoing project on deterioration modeling (see Appendix A.1).
- **Benefits of maintenance:** Delaware and Virginia use Pontis condition states to track the effects of maintenance. But models do not take into account the effects of maintenance, and no other states have quantified the effects of maintenance.
- **Life-cycle cost assumptions:** Except for Virginia and Delaware, states only consider initial costs. See Virginia Appendix D.1 and Appendix D.2.
- **Definition of culvert failure:** Delaware and Virginia define culvert failure as a National Bridge Inventory condition rating of 4 or less, which indicates the culvert is structurally deficient. Michigan defines culvert failure as occurring when traffic can no longer move over the culvert or when water can no longer move through it. Ohio defines culvert failure as a rating of 2 in its asset management system, and Washington as a deterioration of structural integrity to the point that a roadway is at risk of failure.
- **Culvert deterioration research:** See Appendix B.3 for a recently completed Michigan inspection project. Ohio also provided a link to an ongoing project, and Virginia recommended several references.

Literature Review

Information for the literature review (see **Detailed Findings**) is organized into six areas:

- Research in Progress.
- National Resources.
- Deterioration Curves and Models.
- Service Life and Design.
- Benefits of Culvert Maintenance.
- Asset Management.

For the purpose of this **Summary of Findings**, some of these categories have been combined to summarize the research as it relates broadly to MnDOT’s central areas of concern:

- Deterioration Curves and Models.
- Effects of Maintenance on Culvert Service Life.

- Definition of Culvert Failure.
- Research Needs.
- Research in Progress.

Much of the most recent and useful information for this TRS comes from *NCHRP Synthesis 474*: *Service Lives of Culverts* (2) (see **National Resources**), which included a survey that asked state DOTs about their use of culvert deterioration models.

Deterioration Curves and Models

NCHRP Synthesis 474 (2) found that little "recent advancement has been made in refining pipe service prediction models, even for the more common pipe types," although in "the past 15 years there has been significant advancement in understanding the mechanisms of pipe degradation in service." According to a 2008 study (An Asset Management Approach for Drainage Infrastructure and Culverts (32) in **Asset Management**), a survey of state DOTs found that 78 percent of respondents had no deterioration models to predict the service lives of culverts, and 13 percent were developing models. Only two states used models: Virginia had developed its own predictive models, and Delaware was using Pontis deterioration models.

According to *NCHRP Synthesis 474* (2), a survey of DOTs indicated that deterioration models are not sufficiently developed to be useful, and agencies instead use simpler methods, such as estimated service lives categorized by local environmental conditions. For concrete pipes, service life prediction models are:

> … largely empirical and not directly related to the physical mechanisms of degradation or when such degradation reaches a critical point. These methods also have not been recently updated or developed, and they focus predominantly on corrosion and do not consider other degradation mechanisms or joint performance (page 44).

For metal pipes, there are a number of ways of estimating service life that use the California Method to make predictions based on soil pH, resistivity and other factors. A 2015 MnDOT study (Minnesota Steel Culvert Pipe Service-Life Map (13) in **Service Life and Design**) and a 2009 Colorado DOT study (Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials (15) in **Service Life and Design**) employ such methods.

Appendix B (pages 109-123) of *NCHRP Synthesis 474* (2) includes a review of several culvert service life models for both concrete and steel, including models used by Colorado, Florida, Ohio and Utah. Also in **National Resources**, *NCHRP Report 713* (3) includes an overview of culvert deterioration models (pages 37-42), and Appendix F (pages 68-74) of *NCHRP Synthesis 303* (5) provides pipe service life prediction charts.

Only a few studies on deterioration curves for culverts were located, including a 2012 study that develops a deterioration model and applies it to Ohio DOT data (see "Culvert Asset Management Practices and Deterioration Modeling" (9) in **Deterioration Curves and Models**). A 2009 study (Corrugated Steel Culvert Pipe Deterioration (10)) applies a Markov deterioration model to corrugated steel pipes, and a 2008 study ("Estimation of the Remaining Service Life of Culverts" (11)) applies a Weibull model to five material types.

A search of state DOT culvert and drainage manuals did not find information on deterioration models.

Effects of Maintenance on Culvert Service Life

Chapter 5 and Appendix B of *NCHRP Synthesis 474* (2) include estimates of the effect of various culvert rehabilitation techniques on culvert service life. While there is no indication that these estimates have been incorporated into deterioration models, they give a general idea of how many years a treatment can be expected to add to culvert service life.

While several other studies were located related to the benefits of culvert maintenance, most do not estimate the effects of maintenance on culvert service life. However, a 2013 study showed that neural networks could be used to make predictions of culvert conditions that precisely tracked inspection data (see "Neural Network Approach to Condition Assessment of Highway Culverts: Case Study in Ohio" (18) in **Benefits of Culvert Maintenance**).

According to *NCHRP Synthesis 474* (2), less than 40 percent of agencies have a formal culvert asset management system. However, a number of studies address the development of asset management systems for culverts (see **Asset Management**), most of which involve culvert rating systems. A 2009 study ("Culvert Information Management System" (28) by Jay N. Meegoda, the author of many other studies in this area) develops a "framework for inspection and rehabilitation/replacement of corrugated steel culvert pipes" for establishing a culvert information management system. The CIMS is "capable of analyzing decisions to inspect, rehabilitate/replace or do nothing at both project and network levels."

Definition of Culvert Failure

According to *NCHRP Synthesis 474* (2) survey results, among DOTs there "was little consistency in definitions of end of service life, but there appears to be a trend toward using the results of pipe inspection rating systems to set threshold values that trigger maintenance, rehabilitation or replacement" (page 2). *NCHRP Report 713* (3) defines the end of life for culverts as "the age when there is a 50% probability of being in a condition or state when replacement is normally recommended" (page 40). No other resources were found on this topic.

Research Needs

NCHRP Synthesis 474 (2) notes that while deterioration models are not sufficiently developed to be useful, "rapid future progress" should be possible "with research on degradation mechanisms and a better understanding of the progression of deterioration, combined with greater sources of pipe performance data from agency pipe inventories" (page 2). Case studies conducted in 2014 by the Federal Highway Administration (Culvert and Storm Drain Management Case Study—Vermont, Oregon, Ohio, and Los Angeles County (26) in **Asset Management**) found that:

> While deterioration analyses for culverts remain a future goal in all of the systems reviewed, agencies interviewed were finding ways to connect their maintenance and asset management data for culverts. VTrans was connecting culvert management systems with its maintenance management system (MMS) and then linking them with pavement and bridge management systems for infrastructure prioritization. Ohio DOT had begun to develop deterioration models and was also looking at how to link data from its Structure Management System (SMS) to maintenance and its Equipment, Inventory, and Materials System (EIMS).

According to *NCHRP Synthesis 474* (2), DOTs have developed pipe condition rating systems, but these need to be enhanced "to cater for these more realistic definitions of pipe condition and end of service life" (page 45). Fundamental pipe failure models are a major knowledge gap (page 46): "[N]o comprehensive deterioration models have been developed that consider the combined effects of all critical parameters for the major pipe types and define when end of service life occurs or when total failure will occur." See page 48 for a further list of research needs, which include the development of a better understanding of pipe deterioration and failure mechanisms and their incorporation into models.

Research in Progress

An ongoing project by South Carolina DOT (see *Best Practices for Accessing Culvert Health & Determining Appropriate Rehabilitation Methods* (1) in **Research in Progress**) is developing a culvert deterioration model. *NCHRP Synthesis 474* (2) notes that "Florida DOT and several other select agencies have sponsored significant research in the area of pipe degradation, and this research can form the basis for better service life prediction models in the future."

Gaps in Findings and Recommendations

It is unclear how long culvert repairs last and how to quantify deterioration rates by material type or repair method. MnDOT needs to:

- Develop an expanded definition of culvert failure that captures all element failures and that is supported by data and research since agencies do not define culvert failure uniformly. This issue is being discussed at a national level.
- Develop a better understanding of premature culvert failures by collecting data across districts.
- Identify specific causes of failure, including poor soils, slope, capacity and poor installation. To do so, MnDOT needs to:
  - Obtain forensics on why culverts are failing.
  - Learn how to optimize culvert material selection.
- Understand culvert life cycles by obtaining better data and determining failure and deterioration rates. This includes tracking D6 pipe material deterioration.
- Link culvert failures to construction installation inadequacies, including broken joints.
- Establish a data set for repairs, forensics and new pipe materials, including dates when treatments were completed, to update deterioration curves. Sample data can be used to fill in gaps. MnDOT might also consider a project to develop a statistical model that identifies the age profile of its drainage and culvert system.

Next Steps

MnDOT needs data that will help the agency understand and prevent culvert failures, and quantify deterioration rates by material type or repair method. Next steps include:

- Studying numerous current pipe failures to determine why they are failing.
- Collecting data on a sample group of pipes to assign characteristics systemwide, and tracking results by pipe and repair method.
- Exploring staff skill sets for expertise in conducting forensics investigations of culvert failure or proposing a way to assess culvert failure.
- Interviewing construction personnel about the timing and causes of culvert failures.
- Installing mounted cameras for better oversight of culverts.
- Using video detection during culvert inspections to document problems to help show contractors where flaws exist. MnDOT is currently engaged in a research project to enhance its inspection techniques.
- Exploring and refining or changing MnDOT's definition of culvert failure.
- Discussing next steps and assigning responsibilities and time frames at the next hydraulic engineers meeting.

Detailed Findings

Survey of State Practice

Survey Approach

CTC conducted interviews with representatives at seven DOTs: Delaware, Florida, Michigan, Ohio, South Carolina, Virginia, and Washington. Interviews were conducted by phone unless otherwise noted. Interviewees were asked the following questions:

1. Does your agency use deterioration models for culverts? Can you provide documentation of these models?
2. Do your models incorporate the effects of culvert maintenance? If not, have you quantified the benefits of culvert maintenance in other ways?
3. What assumptions do you make when tracking culvert life-cycle costs? How do you factor in a) type of pipe material and b) culvert maintenance?
4. How does your agency define culvert failure? How do you take into account different failure modes (such as material deterioration, unexpected settling due to poor compaction, joint separation and so on)?
5. What research are you aware of regarding culvert deterioration?

Summary of Survey Results

Summaries of interview results are provided below. For reference, an abbreviated version of each question is included before the response.

Delaware

Contact: Jason N. Hastings, Bridge Design Engineer, Delaware Department of Transportation, 302-760-2310, jason.hastings@state.de.us.

1. **Deterioration models:** For culverts with a hydraulic opening of more than 20 square feet, Delaware uses Pontis and its deterioration models to see if culverts have deteriorated in a way that the DOT is used to seeing. Smaller culverts are handled by district maintenance, and deterioration models are not used for them. They are treated as drainage pipes, and maintenance staff looks for depressions over pipes. Delaware is relatively flat and its culverts have under two to three feet of fill, so it's cost-effective to wait to replace them after they have deteriorated significantly.
2. **Benefits of maintenance:** Delaware uses Pontis condition states so that maintenance may result, for example, in changing a condition state from CS3 to CS2.
3. **Life-cycle cost assumptions:** Delaware assumes different life spans for different kinds of culverts (corrugated pipe or concrete) and calculates replacement costs from bid data.
4. **Definition of culvert failure:** Culvert failure is defined as an NBI condition of 4 or less—when metal pipes have significant separation of seams, loss of fill or corrosion, or concrete pipes have joint separation.
5. **Culvert deterioration research:** The interviewee was not aware of any culvert deterioration research.

Florida

Contact: Richard I. Kerr, Bridge Management Inspection Engineer, Florida Department of Transportation, 850-410-5808, richard.kerr@dot.state.fl.us.

Florida DOT responded by email but was not available for a phone interview within the time frame of this project.

1. **Deterioration models:** Florida recently had a research project on deterioration modeling for commonly recognized elements, based on 12 years of element inspection data. See Appendix A.1 and Appendix A.2 for transition probabilities for an Element 240 metal culvert and 241 reinforced concrete

culvert. Florida has a limited number of other types of culverts and so does not have information for these. See Appendix A.3 for a description of the project, Enhancement of the FDOT's Project Level and Network Level Bridge Management Analysis Tools. The full report is available at http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_MNT/FDOT_BDK83_977-01_rpt..pdf.

2. **Benefits of maintenance:** No response.
3. **Life-cycle cost assumptions:** No response.
4. **Definition of culvert failure:** No response.
5. **Culvert deterioration research:** No response.

Michigan

Contact: Therese Kline, Flexible Pipe Specialist, Michigan Department of Transportation, 517-241-0082, klinet@michigan.gov.

1. **Deterioration models:** No. Culverts of 10 to 20 feet in span length are tracked in Michigan DOT's bridge database. Michigan "does not do a good job of managing its culverts at this time." Michigan DOT was looking into research into deterioration models, but has yet been able to fund the project. See Appendix B.1 and Appendix B.2 for information on this project. Michigan was hoping that this project would be assisted by an update to the 1986 FHWA Culvert Inspection Manual: http://isddc.dot.gov/OLPFiles/FHWA/006625.pdf. (The update has not come out yet.) It also planned to make use of Indiana and Ohio documents:
    - http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3075&context=jtrp
    - https://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Culvert%20Management/Pages/Culvert-Management.aspx
2. **Benefits of maintenance:** Michigan DOT has a master data plan for culverts 10 feet wide or larger. These are inspected regularly on a two-year basis. Culverts smaller than 10 feet in diameter are not inspected, and there is no master plan or database for them. As a result, Michigan has seen some catastrophic failures, one that caused the closing of Interstate 75. Michigan has many culverts that are more than 50 years old, and lack of maintenance has led to a lot of problems.
3. **Life-cycle cost assumptions:** None.
4. **Definition of culvert failure:** No formal definition, and opinions differ among staff. The interviewee's opinion is that failure occurs when traffic can no longer move over the culvert, or when what is supposed to move through the culvert can no longer get through it. Cracks that structurally compromise the culvert lead to failures.
5. **Culvert deterioration research:** Michigan completed a research project in 2014 inspecting 800 feet of pipe; see Appendix B.3.

Ohio

Contact: Jeffrey E. Syar, Administrator, Office of Hydraulic Engineering, Ohio Department of Transportation, 614-275-1373, jeffrey.syar@dot.state.oh.us.

1. **Deterioration models:** No. Ohio did research in the 1980s (based on data from the late 1970s) to develop degradation models based on empirical data, and is in the midst of a project on service life prediction, to be completed in August 2016: http://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Lists/Final%20Reports%20All/Item/displayifs.aspx?List=47f3581d-f21c-403b-9358-fea0b008772b&ID=482&ContentTypeId=0x0100BD006C89430C884FB603A74E63BB6849. But Ohio doesn't currently use deterioration models. It has a service life approach predicting metal loss based on site conditions, such as pH. This differs from the California Method. See Appendix C for details.

2. **Benefits of maintenance:** Ohio DOT has not quantified maintenance benefits in other ways. They are in the first round of an inventory and inspection program. When inspection leads to an appraisal rating of a certain value, Ohio DOT conducts maintenance on that asset to improve its appraisal rating. So far Ohio has found a lot of assets that need attention. So maintenance is driven by appraisal ratings from inspection. In most cases, Ohio uses concrete field paving to bring the rating back up.
3. **Life-cycle cost assumptions:** No. Ohio DOT only considers initial costs. Contractors pick their own materials, subject to Ohio DOT's durability analysis (based on site pH rating and material type/thickness).
4. **Definition of culvert failure:** When the asset reaches a general rating value equal to 2. See http://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Culvert%20Management/Culvert%20Management%20Manual/CMM%20-%20July%202015.pdf. Once the asset has a rating of 4, it is inspected annually and put in a district work plan. So it should never get to a condition of 2.
5. **Culvert deterioration research:** Current research on culvert durability is underway at Ohio DOT, and is expected to be completed in August 2016: http://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Lists/Final%20Reports%20All/Item/displayifs.aspx?List=47f3581d-f21c-403b-9358-fea0b008772b&ID=482&ContentTypeId=0x0100BD006C89430C884FB603A74E63BB6849.

South Carolina

Contact: David Cook, Assistant Maintenance Engineer, South Carolina Department of Transportation, 803-737-1290, cookdb@scdot.org.

South Carolina DOT responded by email but was not available for a phone interview within the time frame of this project.

1. **Deterioration models:** No. For nonbridge length culverts, South Carolina performs manual assessments to determine culvert conditions. It is still in the process of developing the maintenance and rehabilitation program to address the deficiencies identified in the assessments.
2. **Benefits of maintenance:** No response.
3. **Life-cycle cost assumptions:** No response.
4. **Definition of culvert failure:** No response.
5. **Culvert deterioration research:** No response.

Virginia

Contact: Adam Matteo, Assistant State Structure and Bridge Engineer, Bridge Maintenance, Virginia Department of Transportation, 804-786-5171, adam.matteo@vdot.virginia.gov.

1. **Deterioration models:** No for pipes under 100 feet in diameter. Yes for culverts meeting NBI criteria for inspection (about 8,000 total) via Pontis: See Appendix D.1 and Appendix D.2. For its tens of thousands of smaller pipes under 10 feet in diameter, it uses a service life rating system based on site conditions, such as pH. (CTC is awaiting documentation and will forward upon receipt.)
2. **Benefits of maintenance:** Virginia DOT's models do not incorporate the effects of culvert maintenance, and they have not quantified maintenance benefits in other ways.
3. **Life-cycle cost assumptions:** Virginia DOT bases its models on the current valuation of structures. It looks at depreciation caused by deterioration. See Appendix D.1 and Appendix D.2.
4. **Definition of culvert failure:** A condition rating of 4 or less, which indicates it is structurally deficient. These ratings are based on a nationally published standard from FHWA.
5. **Culvert deterioration research:** Virginia DOT recommended:

    - Proposed Practice for Alternative Bidding of Highway Drainage Systems, NCHRP 801: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_801.pdf

- Guidance for Design and Selection of Pipes, NCHRP Project 20-07, Task 264: http://design.transportation.org/Documents/NCHRP20-07(264)_Final%20Report%20for%20AASHTO.pdf
- *Service Life of Culverts, NCHRP Synthesis 474* (2): http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_474.pdf
- FHWA Construction Program Guide—Culvert Selection: https://www.fhwa.dot.gov/construction/cqit/culvert.cfm
- FHWA Durability Analysis of Aluminized Type 2 Corrugated Metal Pipe: https://www.fhwa.dot.gov/publications/research/infrastructure/hydraulics/97140/97140.pdf
- FHWA Culvert Inspection Manual: http://isddc.dot.gov/OLPFiles/FHWA/006625.pdf
- USDA Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology: http://www.fs.fed.us/t-d/pubs/pdfpubs/pdf11771810/pdf11771810Pdpi72.pdf

Washington

Contact: Julie Heilman-Suarez, Interim State Hydraulics Engineer, Washington Department of Transportation, 509-577-1703, suarezj@wsdot.wa.gov.

1. **Deterioration models:** No. Culverts are inspected every two years by maintenance staff for scour, culvert deterioration and abrasion. Inspectors fill out a form describing the culvert: The system is entirely qualitative and does not use numeric ratings. Inspectors' reports are stored in a database.
2. **Benefits of maintenance:** Washington DOT has not formally quantified the benefits of culvert maintenance. It relies on engineering experience and judgment.
3. **Life-cycle cost assumptions:** Washington DOT is not tracking life-cycle costs. Its culvert inventory is just a physical inventory.
4. **Definition of culvert failure:** When any part of the structural integrity has deteriorated such that there is a risk to failure of the roadway.
5. **Culvert deterioration research:** The interviewee was not aware of any culvert deterioration research.

Research in Progress

1. Best Practices for Accessing Culvert Health & Determining Appropriate Rehabilitation Methods, South Carolina Department of Transportation, expected completion date: August, 2016.
Citation at http://rip.trb.org/view/1346851
From the abstract:

> The overarching goal of this research project is to provide technical guidance to the South Carolina Department of Transportation (SCDOT) in effectively managing their culvert infrastructure. Four specific objectives identified are: (1) Develop guidance on selecting reliable and cost-effective condition assessment techniques by SCDOT; (2) Develop a risk-based model for prioritizing culvert rehabilitation based on the condition rating data recorded by SCDOT; (3) Develop a deterioration model to predict the future condition of culverts in order to optimally spend limited resources available on inspecting and repairing only those culverts that are critical and closer to failing; and (4) Develop a decision-making tool for selecting an economical and most effective culvert repair method based on condition rating and other culvert characteristics such as age, material, diameter and etc.

National Resources

2. NCHRP Synthesis 474: Service Life of Culverts, Michael Maher, Gregory Hebeler and Andrew Fuggle, 2015.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_474.pdf
This project surveyed North American transportation agencies on the current state of the practice regarding culvert service lives and also involved a literature review. According to the report, while little "recent advancement has been made in refining pipe service prediction models, even for the more common pipe types,"

in "the past 15 years there has been significant advancement in understanding the mechanisms of pipe degradation in service." Appendix A (see page 53 of the report) includes full survey results.

Highlights of results include (pages 1-2 of the report):

- **Deterioration models:**
    - Current models are not useful, and agencies do not use them, preferring simpler methods:
        - "The current deterioration models, while providing broad guidance on pipe type suitability, are not sufficiently developed to allow a meaningful comparison of alternatives."
        - "Less than a quarter of respondents indicated that they had developed or improved pipe durability prediction models. Those that have developed prediction models include DOTs that are subject to extremely variable or extreme environmental conditions."
        - Most agencies "predict service life using case studies, internal research results, or default estimated service life values holistically or categorized by local environmental conditions, rather than published models."
        - "A further limitation is the inability to relate a defined end-of-service-life indicator to ultimate failure of the pipe system. Ideally, pipe deterioration models need to be able to model the progressive loss of pipe condition from installation to final failure. With this type of model, it would be possible to evaluate the cost-effectiveness of maintenance activities, rehabilitation options, and full pipe replacement and to assist in establishing when these interventions are needed."
    - There has been little recent advancement in service life prediction models, although "rapid future progress" should be possible "with research on degradation mechanisms and a better understanding of the progression of deterioration, combined with greater sources of pipe performance data from agency pipe inventories."
        - "Agencies are developing methods for predicting the service life of culverts, but developments are generally concentrated within a core group of agencies where this topic is regarded as a high research priority."
        - "Florida DOT and several other select agencies have sponsored significant research in the area of pipe degradation, and this research can form the basis for better service life prediction models in the future."
- **Defining culvert failure:** "There was little consistency in definitions of end of service life, but there appears to be a trend toward using the results of pipe inspection rating systems to set threshold values that trigger maintenance, rehabilitation, or replacement."
- **Asset management and rehabilitation:** "Less than 40% of agencies had a formal culvert asset management system in place. In situ pipe rehabilitation is becoming routine, with only two agencies indicating that they have not used it. Sliplining was the most common technology in use."

Design/Material Service Life

Chapter 2 gives a synthesis of the state of the practice. Survey results show that criteria for establishing a design service life include (page 5 of the report):

- Average daily traffic
- Functional classification of roadway
- Design service life of nearby structures
- Financial cost of future replacement/rehabilitation
- Consequences/risks of premature failure

However, "the large number of 'other' responses to the survey question on [design service life] indicate variability across North American practice in this area, and that a number of agencies are not using the concepts of design and material service lives to evaluate and select culverts" (page 5 of the report).

Most agencies make assumptions about material service lives, and many collect site-specific environmental data and have maps "that indicate regions of environmentally aggressive conditions" (page 5 of the report).

Overall:

> Although some DOTs and industry have guidelines on defining design service life for various highway applications, a standard approach for this process does not exist. On a simple level, most agencies relate design service life to the highway classification or the strategic importance of the route. Thus, design service lives of 25, 50, 75, or 100 years can be assigned (page 47 of the report).

Defining Culvert Failure
From page 6 of the report:

> Multiple factors are considered by most agencies in defining the end of service life, with the most common being section failure (crushing, buckling, de-bonding), cracking, joint performance, and deflection (flexible pipes only). A number of agencies use inspection rating systems to quantify serviceability, and have threshold values that trigger maintenance, rehabilitation, or replacement.

Estimating Service Life Based on Deterioration Factors and Materials
Chapter 3 (pages 8-18) defines degradation mechanisms for culverts, including corrosion, pH, resistivity, sulfates, chlorides, microbes and abrasion. Chapter 4 (pages 19-33) reviews the effect of pipe materials on service life, including a review of various agencies' expected service lives for pipes of various materials.

Chapter 7 (page 43) notes that life-cycle cost analysis:

> … may remain limited until reliable data on maintenance costs incurred from traditional and lifecycle cost projects become available. The significant increase in the use of culvert rehabilitation and repair techniques as opposed to culvert replacements will provide an opportunity for these data to be compiled in the coming decade.

Deterioration Models
Concerning service life prediction models, the report concludes (from page 44 of the report):

> The majority of the available service life prediction models for concrete pipes are largely empirical and not directly related to the physical mechanisms of degradation or when such degradation reaches a critical point. These methods also have not been recently updated or developed, and they focus predominantly on corrosion and do not consider other degradation mechanisms or joint performance.

A "range of methods exist for predicting the service life of metal pipes," all variation on the California Method, and "corrosion rates for metal pipes are probably the best defined" (page 44). DOTs have developed pipe condition rating systems, but these need to be enhanced "to cater for these more realistic definitions of pipe condition and end of service life" (page 45).

Fundamental pipe failure models are a major knowledge gap (pages 46-47 of the report):

> Although culvert research is an active area and progress has been made in understanding pipe deterioration mechanisms, still no comprehensive deterioration models have been developed that consider the combined effects of all critical parameters for the major pipe types and define when end of service life occurs or when total failure will occur.
>
> …
>
> The current service prediction models are generally based on a selected end-of-service-life indicator and only consider one distress mode, typically corrosion, to predict expected service life. Where combined abrasion and corrosion are present, the model no longer applies. Thus, to prolong service life resulting from

corrosion, coatings can be considered; however, at what stage is invert paving required and what are the economics of selecting various invert paving options? The current deterioration models, while providing broad guidance on pipe type suitability, are not sufficiently developed to allow a meaningful comparison of alternatives.

…

To date, the significant research progress that has been made over the past 15 years in understanding the various deterioration mechanisms for a range of pipe types has yet to be incorporated into improving the overall pipe deterioration models. … A lack of comprehensive failure models exists for all pipe types, although metal and concrete pipes have initial limited working models.

Appendix B (pages 109-123) includes a summary of service life calculation methods, including:

For concrete pipes:

- Hurd model
- Hadipriono model
- Ohio DOT model
- Florida DOT model

For steel pipes:

- California Method
- American Iron and Steel Institute method
- Federal Lands Highway method
- Colorado DOT method
- Florida DOT method
- National Corrugated Steel Pipe Association recommendations
- Utah DOT method

Appendix C (pages 124-133) includes examples of service life calculations using various methods.

Effects of Rehabilitation on Service Life

Chapter 5 (pages 34-38) reviews pipe rehabilitation methods with some estimated effects on service lives:

- Invert paving: "Minnesota DOT identified a case study where invert paving had lasted longer than 25 years (Minnesota DOT 2012). Ohio DOT assumes a 20-year add-on service life for concrete paving."
- Sliplining: "Properly sliplined culverts should provide the full service life anticipated from the type of pipe used in the sliplining. Thus, it is generally equivalent to full pipe replacement in terms of future service life."
- Spirally wound liner: "Caltrans (2013) use spirally wound liners for both flexible and rigid pipes to provide a corrosion barrier suitable to meet a 50-year design service life for abrasion levels 1 through 3."
- Sprayed-on liner (cementitious/shotcrete): "If properly installed, shotcrete and CSC liners with durable and high-strength concrete mixes enhance the structural capacity of the pipe and provide serviceable lives that exceed 50 years."
- Sprayed-on liner (epoxy): "Epoxy lining systems are relatively new and no data are available on life expectancy."
- Cured-in-place pipe: "Winnipeg, Canada, was one of the early adopters of CIPP technology in North America when it began relining its sewer pipes in 1978. Video inspection and sampling of the CIPP liners after 34 years of service has confirmed that the liners' condition are still excellent with no evidence of material degradation or induced stress on the liners (Macey and Zurek 2012) (Figure 33)."
- Pipe bursting/splitting: "The service life expectations for pipe replacement by way of pipe bursting is equivalent to that for the replacement pipe type and material."

Appendix B of the report includes a method for calculating additional service life due to coatings (page 120) based on a summary table from the Ministry of Transportation of Ontario.

Research Needs

A discussion of research needs, which include the development of a better understanding of pipe deterioration and failure mechanisms and their incorporation into models, is provided on page 48.

3. NCHRP Report 713: Estimating the Life Expectancies of Highway Assets, Paul D. Thompson, Kevin M. Ford, Mohammad H. R. Arman, Samuel Labi, Kumares C. Sinha and Arun M. Shirole, Vol. 1, 2012.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_713v1.pdf
Section 4.1.1 (beginning on page 37 of the report) provides an overview of culvert deterioration models. This section includes end-of-life criteria for culverts as "the age when there is a 50% probability of being in a condition or state when replacement is normally recommended" (page 40).

4. Guidance for Design and Selection of Pipes, NCHRP 20-07(264), April 2011.
http://design.transportation.org/Documents/NCHRP20-07%28264%29_Final%20Report%20for%20AASHTO.pdf
This research developed a recommended standard for selecting pipe materials based on sound, scientific research to meet transportation needs for providing durable, safe and economical products. It includes guidelines for determining pipe service lives.

5. NCHRP Synthesis 303: Assessment and Rehabilitation of Existing Culverts, David Wyant, 2002.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_303.pdf
This report summarizes the state of the practice of pipe assessment, the selection of appropriate repair or rehabilitation methods, and the management aspects of a pipe program. Research for the report included a literature review and a survey of local, state and federal transportation agencies. The report emphasizes the importance of record keeping form inspections for generating deterioration curves (page 32) and noted that Maine DOT had the most comprehensive system for record keeping (page 34). Appendix F (pages 68-74) provides pipe service life prediction charts.

Deterioration Curves and Models

6. "Influence of Soil Models on Performance of Buried Culverts," Michael G. Katona, *TRB 94th Annual Meeting Compendium of Papers*, Paper #01550057, 2015.
Citation at http://trid.trb.org/view/1336687
This study examines the effect of soil stiffness on the structural distress of buried culverts using three soil models:

> Specifically, graphical charts show each soil model's influence on the American Association of State Highway and Transportation Officials (AASHTO) design criteria for corrugated steel, reinforced concrete and plastic pipes under deep burial and HS-20 live load conditions. As expected, the 8-parameter Duncan/Selig soil model exhibits the best performance in replicating the laboratory experimental data and in predicting the blind experimental tests. With regard to the comparative finite element studies, the Mohr/Coulomb plasticity model produces results that are nearly indistinguishable from the linear elastic model because the surrounding soil mass around the culvert does not experience plastic shear failure due to large confining pressures. In contrast, the Duncan/Selig model generally predicts greater distress in all pipe types implying it is more conservative and produces safer culvert designs.

7. "Simulation of Behavior of In-Service Metal Culverts," Kyong Y. Yeau, Halil Sezen and Patrick J. Fox, *Journal of Pipeline Systems Engineering and Practice*, Vol. 5, Issue 2, 2014.
Citation at http://trid.trb.org/view/1277074
From the abstract:

> As part of an experimental program, a large number of in-service culverts were tested to investigate the influence of several parameters on field performance of culverts. These parameters included cover depth, load application, size, shape, and other properties of corrugated metal culverts. Response of 14 test culverts was simulated using a two-dimensional finite element program and a three-dimensional finite difference program. Deflections predicted from the two-dimensional analyses were larger than the deflections measured in the field. However, the experimental and calculated thrust forces were similar. Deflections and thrust forces predicted from the three-dimensional analysis were similar to the experimental results. The critical factors affecting the response of the culverts include cover depth, culvert size, metal thickness, and elastic modulus and other properties of backfill soil. The influence of these parameters on the culvert behavior is investigated through numerical simulations using the established modeling properties.

8. Modeling the In Situ Performance of Culvert Joints in a Pavement Structure (poster), Roberto Soares, Farukh Sharipov, Colin Wandzura, Brent Marjerison and Curtis Berthelot, 2013 Conference and Exhibition of the Transportation Association of Canada.
http://conf.tac-atc.ca/english/annualconference/tac2013/poster4/soares.pdf
From the abstract:

> This study employed a computational road model to investigate the strain behaviour along the culvert-road soil interface and to examine the mechanisms by which culvert joints pull apart. Two pavement structures were modeled in two different moisture conditions: a primary and secondary road structure, in both wet and dry moisture states. The secondary road structure in a wet moisture condition state had overall higher magnitudes of shear and horizontal strains compared to the other road structures and condition states. From a dry to wet moisture condition state on the secondary road, shear strain increased by 119%, the horizontal strain in the longitudinal direction increased by 114%, and the horizontal strain in the transverse direction increased by 116%. This research showed that the horizontal strain in the longitudinal direction was greater in magnitude for the wet moisture condition states in comparison to the dry moisture condition states.

9. "Culvert Asset Management Practices and Deterioration Modeling," Ossama Salem, Baris Salman and Mohammad Najafi, *Transportation Research Record 2285*, pages 1-7, 2012.
http://trrjournalonline.trb.org/doi/abs/10.3141/2285-01?journalCode=trr
This study reviews the literature on factors affecting culvert performance as well as current culvert asset management practices by transportation agencies. It then proposes a "preliminary deterioration model that will allow decision makers to identify significant factors that affect deterioration of metal culverts and prioritize inspection procedures." The model uses a "binary logistic regression with a forward stepwise variable selection method on data obtained from the Ohio Department of Transportation."

10. Corrugated Steel Culvert Pipe Deterioration, Jay N. Meegoda and Thomas M. Juliano, New Jersey Department of Transportation, August 2009.
http://transportation.njit.edu/nctip/final_report/CulvertPipeDeterioration.pdf
This study "provides the basis for developing a comprehensive plan for inspection, cleaning, condition assessment and prediction of remaining service life of CSCP (Corrugated Steel Culvert Pipe)." This includes a rating system based on corrosion, erosion, bed load, pH, culvert size and other factors. Researchers also use a Markov deterioration model "to predict the future condition state of new CSCP in urban and rural settings." Appendix I (pages 67-70) addresses the Markov deterioration model but does not take into account the effects of rehabilitation.

11. "Estimation of the Remaining Service Life of Culverts," Jay N. Meegoda, Thomas Juliano and Sameer Wadhawan, *TRB 87th Annual Meeting Compendium of Papers DVD*, Paper #08-1523, 2008.
Citation at http://trid.trb.org/view/848077
From the abstract:

> A five state Condition State model that is used to express the extent of the culvert deterioration, is coupled with a reliability analysis based upon the Weibull model to estimate the remaining service life of the culvert. The cumulative distribution function of failure is normalized by the design life in order to collapse the decay curve into a single curve for the five material types. Based on the inspection data it was concluded that the proposed theory could represent the culvert performance data for five different culvert material types used in New Jersey. The proposed theory represents a preliminary approach to estimation of remaining service life of culverts. Future research is expected to focus on field studies to obtain the necessary cost and performance parameters for deteriorating culvert pipes and to perform a statistical analysis of the sample.

12. "Finite Element Study of Stability of Corroded Metal Culverts," Mohamed El-Taher and Ian D. Moore, *Transportation Research Record 2050*, pages 157-166, 2008.
Citation at http://trid.trb.org/view/848829
From the abstract:

> This study … examines the influence of corrosion on the stability of corrugated steel culverts. Corrosion in the lower half of the structure is considered, including a range of losses in wall thickness and lateral extents. Changes in the factor of safety against yield are assessed as corrosion develops, as are changes in culvert resistance to buckling failure. For the five specific design cases considered, the governing design criterion was stability against yield, and the factor of safety against yield was found to decrease almost in proportion to wall thickness (when maximum wall thrust within the corroded zone was considered). This decrease occurred because the corroded metal culverts experienced little change in the distributions of thrust or moment as a result of local losses in wall thickness. While the results presented are purely theoretical, they provide a starting point for an appreciation of the influence of metal culvert deterioration and can guide future research, including physical test programs.

Service Life and Design

13. Minnesota Steel Culvert Pipe Service-Life Map, Barbara Heitkamp and Jeffrey Marr, Minnesota Department of Transportation, June 2015.
http://www.dot.state.mn.us/research/TS/2015/201531.pdf
Researchers used the California Method with STATSGO data to develop maps of the service lives for 18-, 16-, 14-, 12-, 10- and 8-gage galvanized and aluminized steel pipe in locations across Minnesota, based on pH and resistivity. STATSGO pH data were verified by field measurements.

14. "The Influence of Design Variables and Environmental Factors on Life-Cycle Cost Assessment of Concrete Culverts," D. K. Panesar and C. J. Churchill, *Structure and Infrastructure Engineering*, Vol. 9, Issue 3, pages 201-213, 2013.
Citation at http://trid.trb.org/view/1222930
From the abstract:

> The objective of this article is to evaluate the influence of material, structural design variables and exposure conditions on the service life and cost effectiveness of precast concrete culverts in Canada. This investigation will assist practicing engineers to account for long-term performance and integrate life cycle analysis into design and construction decisions. The design variables considered in this study include the percentage of ground granulated blast furnace slag (GGBFS) as cement replacement, reinforcing steel cover depth and culvert size. This study proposes the usage of a life-cycle cost assessment approach to compare different culvert designs on an economic basis which accounts for the design variables and the impact of CO2 production and uptake over the life of a culvert from cradle to grave. Analysis of each culvert scenario includes the cost of the initial production of CO2 during the manufacturing process as well as the cost

savings that were incurred due to the uptake of CO2 through carbonation processes. Overall, the present cost of the culverts is controlled by the GGBFS content and the reinforcing steel cover depth while carbonation processes have a relatively small economic impact.

15. Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials, Albert Molinas and Amanullah Mommandi, Colorado Department of Transportation, 2009.
https://www.codot.gov/programs/research/pdfs/2009/culvetrpipes.pdf/view
From the abstract:

> In this research effort, literature surveys and reviews of the current methodologies employed by various state departments of transportation (DOTs) were conducted. The literature survey identified the pertinent parameters in estimating the service life of various pipe materials. Following the literature survey, field visits to culvert sites were made to collect data. Selection of culvert sites was jointly made by engineers from Staff Bridge, Staff Hydraulics, and members of the study panel. Field surveying of 21 sites where failed pipe installations were observed was conducted in Colorado along I-70, I-25, and SH 58 to obtain a good cross-section of soil type samples. At these sites, soil and water samples were obtained and soil resistivities were determined using applicable Colorado Procedures, AASHTO test methods, or ASTM test methods. Soil and water samples from these sites were analyzed for sulfate/chloride level concentrations, and pH levels. Relevant culvert inspection data from Staff Bridge inspection programs were obtained and used in the analysis where needed. Data collected from literature searches, the Staff Bridge database, actual field surveys, and other unbiased reliable sources were analyzed. The service life was correlated with various parameters including type of material, pH level, chloride and sulfate level concentrations, specific resistivity, abrasion data (steep pipe slopes, high sediment loads, high flow velocity in pipes, etc.) and other factors that could have influenced premature deterioration or failures. A new service life chart for steel pipes was developed based on the information collected from the field observations and data analysis. Data from Colorado pipe failure cases were used in relating service life of pipes to soil resistivity. Pipe failure criteria were established in accordance with the ongoing culvert evaluation procedure along I-70 and I-25. For the steel pipe failure cases along I-70 and I-25, the previously published service life predictors for steel pipes deviated from observations by as much as 10 times. Service life multipliers to account for steel pipe thickness effects had been greatly exaggerated. For aluminum pipes, the research identified chloride and sulfate concentrations as factors that reduced the service life of these pipes dramatically. It is anticipated that the results of this study will be adopted by cities, counties, and other states where selection of pipe materials for corrosion/abrasion resistance is required during the design and construction of transportation projects. Training courses provided to the Colorado DOT engineering community and to the general consulting engineering community can be used as an implementation tool.

Benefits of Culvert Maintenance

16. "Role of Grout Strength and Liners on the Performance of Slip-Lined Pipes," Trevor Smith, Neil Hoult and Ian D. Moore, *Journal of Pipeline Systems Engineering and Practice*, Vol. 4, 2015.
Citation at http://trid.trb.org/view/1350985
From the abstract:

> The current research seeks to better understand the performance of slip-lined systems by (1) characterizing the properties of a low-strength and a high-strength grout; (2) conducting a series of pipe tests to determine the load-carrying capacity and stiffness of a corrugated steel pipe and pipes that have been rehabilitated with slip liners; (3) understand the impact of grout strength and the liner on pipe stiffness and strength; and (4) determine the level of composite action in the pipe system by using a plasticity approach to estimate the load-carrying capacity of the system. The pipes rehabilitated with low-strength grout had increased strength (three times greater) and stiffness (eight times greater) versus an unrehabilitated pipe, whereas the specimens rehabilitated with high-strength grout showed higher increases in both load-carrying capacity (ten times greater) and stiffness (50 times greater) over the unrehabilitated pipe. The high density polyethylene (HDPE) liner had no impact on the load-carrying capacity of the specimens with high-strength grout and required large diameter changes to enhance the load-carrying capacity of low-strength grout

specimens. A plasticity approach was used to estimate the load-carrying capacity of the specimens and indicated that for these tests, composite behavior between the grout and the corrugated steel pipe was developed.

17. "Experimental Examination of Deteriorated and Rehabilitated Corrugated Metal Culverts Subjected to Service Load," Shaurav Alam, Sarkar Sayem, Steven Aaron, Jacob Pierce, Erez Allouche and Robert McKim, *TRB 93rd Annual Meeting Compendium of Papers*, Paper #14-5578, 2014.
Citation at http://trid.trb.org/view/1290022
From the abstract:

Many culverts in North America are in various states of deterioration resulting in diminished structural and/or hydraulic capacities. A culvert's failure could result in road subsidence or even collapse, leading to serious consequences for vehicular traffic and public safety. The goal of this research is to establish distress and failure mechanisms for rehabilitated culverts made from corrugated metal and concrete pipes, as well as liner-culvert-soil interaction mechanisms, in support of the development of sound design methodologies for these repairs. A series of tests were performed on deteriorated 24-inch metal culverts prior to and following rehabilitation using various trenchless lining methods. This research employed either exhumed deteriorated corrugated metal pipe culverts or corrugated metal pipes deteriorated mechanically by removing 25 percent of the metal within a pre-determined arc along the lower half of the culvert. Culvert specimens were carefully bedded, backfilled, and compacted in soil within a test chamber, and then loaded using a pneumatic loading system to simulate deep burial conditions. Deformation and strains were measured at multiple locations around the circumference of the culvert's structure during application of load, while earth pressure cells recorded stresses in the embedment zone. The deformed culvert was then rehabilitated using a cured-in-place liner, a slip liner, or a spiral-wound liner, and external load was re-applied. Numerical simulation of culvert was also performed using ANSYS. Responses of the deteriorated and rehabilitated soil-pipe systems were recorded and compared. The results revealed that the degree of compaction of the bedding materials plays a critical role in determining the stress distributed on the culvert.

18. "Neural Network Approach to Condition Assessment of Highway Culverts: Case Study in Ohio," O. Tatari, S. Sargand, T. Masada and B. Tarawneh, *Journal of Infrastructure Systems*, Vol. 19, Issue 4, pages 409-414, 2013.
Citation at http://trid.trb.org/view/1277934
From the abstract:

Instead of inspecting each culvert every 5 years, this study presents a more intelligent approach to predict the condition of each culvert. An artificial neural network (ANN) model is built to assess the condition of the culverts based on culvert inventory data. The overall condition-rating predictions are compared with the condition rating based on manual inspection. The results of this study have shown that ANN was able to predict culvert adjusted overall rating with high precision, as the course of action score prediction rate was 100%. Sensitivity analysis of the ANN model is provided to assess the effect of variables. The goal of this study is to show that more intelligent culvert-management systems could be devised by taking advantage of artificial intelligence.

19. "Culvert Asset Management and Relining Case Study in Saskatchewan," Brian Taylor, Curtis Berthelot, Roanne Kelin, Rock Gorlick, Brent Marjerison and Mark Theetge, *TRB 90th Annual Meeting Compendium of Papers*, Paper #11-2092, 2011.
Citation at http://trid.trb.org/view/1092301
From the abstract:

This paper summarizes the pilot use of high density polyethylene (HDPE) pipe liners in Saskatchewan culvert rehabilitation and highlights the benefits of using HDPE pipe liners. To investigate alternate culvert rehabilitation methods, [the Saskatchewan Ministry of Highways and Infrastructure] piloted the use of a quick connect type HDPE smooth walled culvert lining system. It was found that field assembly and installation of the HDPE culvert liners was efficient, with no specialized or expensive equipment required.

> Construction occurred with minimal disruption to traffic. The culvert liner's joint fasteners enabled the HDPE pipe to be installed during the winter season. The HDPE liners and grouting increased the structural integrity of the culvert and eliminated surrounding voids in the granular backfill material around the CSP culvert. Finally, the smooth walled HDPE pipe liners improved flow capacity. Culvert relining was a cost effective means of rehabilitating existing culverts relative to conventional culvert remediation or replacement methods.

20. "Long-Term Monitoring of Culvert Load Reduction Using an Imperfect Ditch Backfilled with Geofoam," Liecheng Sun, Tommy C. Hopkins and Tony Beckham, *Transportation Research Record 2212*, pages 56-64, 2011.
Citation at http://trid.trb.org/view/1091620
From the abstract:

> Rigid culverts resting on unyielding foundations are frequently required in Kentucky for routing streams beneath highway embankments because of shallow depths to bedrock, rolling terrain, numerous streams, and the need to use high fills, which create large vertical stresses. Expensive structures are usually required. To find a way to reduce large vertical pressures, ultralightweight geofoam was placed in a 2-ft-thick trench above a reinforced, rigid concrete box culvert resting on an unyielding foundation at a roadway site in Kentucky. In situ measurements of stresses, strains, and geofoam settlements obtained over 5 years showed that geofoam was an ideal compressible material to use in the imperfect trench. At two culvert sections where geofoam was used, vertical pressures were reduced to about 10% of the normal pressures measured at the top of a culvert section where geofoam was not used. Stresses on top of two culvert sections where geofoam was used remained relatively stable after final grade elevation was reached. Earth pressures on the sidewalls of all three sections of the culvert did not change significantly after completion of the fill and were much lower than the vertical pressures measured in the culvert section without geofoam. Geofoam settlement of 60% has been recorded. Settlement behavior of the geofoam showed that movement of the soil prism above the imperfect trench was rapidly decreasing with increasing time and suggested that the reduced vertical stresses observed under the geofoam culvert sections could remain throughout the culvert design life.

21. "The Rehabilitation of Corrugated Metal Culverts," R. Heywood and R. Pritchard, *Austroads 8th Bridge Conference*, Sydney, New South Wales, Australia, 2011.
Citation at http://trid.trb.org/view/1138154
From the abstract:

> This paper considers the rehabilitation of deteriorated corrugated metal culverts using plastic liners, spirally wound and grouted into existing culverts. This process, which extends culvert life without the costly disruption of road closures, was originally developed as an aid to sewer rehabilitation, but has been trialled in several states to rehabilitate culverts. Observations drawn from case studies and soil-structure interaction finite element analyses point to significant differences in behaviour between flexible buried culverts and the culvert once it has been rehabilitated using a grouted liner. This highlights the need for a rehabilitation design procedure that is consistent with the behaviour of grouted liners rather than flexible buried culverts.

22. In-Situ Culvert Rehabilitation: Synthesis Study and Field Evaluation, Travis Hollingshead and Blake P. Tullis, Utah Department of Transportation, June 2009.
http://utah.ptfs.com/awweb/awarchive?type=file&item=27347
From the abstract:

> This synthesis study evaluated culvert rehabilitation (repair) methods involving trenchless technologies that may be appropriate for use in Utah. This report is not intended as a replacement for installation manuals provided by the manufacturers but rather provides a brief description of each method and its installation procedures, and highlights the advantages and disadvantages of each. Segmental lining is cost effective in Utah and the most common method of culvert rehabilitation in most western state highway culverts. Cured-in-place pipe and fold-and-form methods are also common but the costs are higher than segmental lining.

The Department of Transportation (DOT) maintenance personnel can often carry out segmental lining, while contractors with specialized skills and equipment are required for all other methods. This report also presents a survey of culvert relining project costs (western states) and a discussion on burial depth limitations and end treatments. The information provided was obtained through a literature review, surveys of various western state DOTs and interaction with the Utah Department of Transportation (UDOT). A flip chart and installation video were developed for segmental lining as part of this study, with the majority of effort coming from UDOT personnel. Table 1 at the end of the report summarizes the main disadvantages, advantages, and limitations for each culvert relining method.

Asset Management

23. "Long-Term Maintenance of Culvert Networks," Jay N. Meegoda and Zhenting Zou, *Journal of Pipeline Systems Engineering and Practice*, Vol. 1, 2015.
Citation at http://trid.trb.org/view/1340357
From the abstract:

> This manuscript presents a discussion on budget planning for maintenance and rehabilitation scheduling and optimization of a culvert network. Any maintenance and rehabilitation expenditure should be justified such that net increase in the asset value should be more than the cost of rehabilitation, where the net worth of an asset should be based on performance rather than on book value. Government standards require owners to maintain or improve the overall condition state of their infrastructure systems with substantial annual investment. In this paper, three methods were proposed to compute the long-term annual investments for culvert networks. They are modified worst first method, network optimization approach, and estimation by the maximum deterioration rate. The performance of a 15-culvert system was simulated using the above methods. Based on the simulation results, the modified worst first method is computationally intensive but provides the optimum budget. The method using maximum deterioration rate provides the lower bound value and should be used as the absolute lowest value that should be allocated. The optimization method uses computer programming and provides an upper bound value for small networks. It is anticipated that for large culvert networks the network optimization approach can be used to provide reasonable long-term annual budgets. Out of the three methods, the modified worst first method provided a minimum long-term annual budget of $9,000 consistent with the government requirements.

24. "Developing a Methodology to Assess and Prioritize Culvert Conditions on County Roads," Wesley Werbelow and Khaled Ksaibati, *Transportation Research Record 2474*, pages 203-212, 2015.
Citation at http://trid.trb.org/view/1360331
From the abstract:

> Through an examination of the inspection procedures of other agencies across the nation and the Wyoming Department of Transportation's bridge inspection procedure, a comprehensive methodology for obtaining an overall pipe rating was developed. This methodology was implemented in Goshen County in Wyoming as a case study. The information and results from this study will be presented to various entities to facilitate statewide implementation. Local agencies in other states can implement the developed methodology with minor adjustments to reflect local conditions.

25. Processes of Small Culvert Inspection and Asset Management, Justin D. Bowers, Samuel R. Magers, Jennifer Pyrz and Darcy M. Bullock, Indiana Department of Transportation, 2014.
Citation at http://trid.trb.org/view/1322782
From the abstract:

> Proper drainage is essential for pavement to maximize life expectancy and minimize maintenance. Culverts are a critical asset to facilitate drainage. As with many assets, culverts deteriorate with age and require regular inspection. It is important to have a formalized process of inventory and inspection that is efficient and can effectively support culvert asset management. The current culvert inspection and asset management processes for the Indiana Department of Transportation (INDOT) have been modeled over the years on the bridge inspection process and were recently evaluated. A study was undertaken to further evaluate the

current culvert asset management practices. Approximately 700 small culverts and catch basins were visited and evaluated using both the traditional culvert inspection practices and a revised asset management evaluation scale. The paper summarizes the findings of this evaluation and concludes by making recommendations for process improvements. These recommendations include the addition of photos to the culvert database, a revised rating scale, advanced planning of inspection schedules, a formalized process for culvert reassessments, the creation of a separate catch basin inlet inventory, various improvements to the inventory process, and a dedicated staff to complete inspections efficiently. It is also noted that building a reliable database will show historical trends and can eventually lead to a study of small culvert inspections and culvert longevity, which will lead to improved asset management.

26. Culvert and Storm Drain Management Case Study: Vermont, Oregon, Ohio, and Los Angeles County, Marie Venner, Federal Highway Administration, 2014.
https://www.fhwa.dot.gov/asset/pubs/hif14008.pdf
This study includes case studies of culvert systems for three states (Ohio, Oregon, and Vermont) and one county (Los Angeles). From the executive summary:

> While deterioration analyses for culverts remain a future goal in all of the systems reviewed, agencies interviewed were finding ways to connect their maintenance and asset management data for culverts. VTrans was connecting culvert management systems with its maintenance management system (MMS) and then linking them with pavement and bridge management systems for infrastructure prioritization. Ohio DOT had begun to develop deterioration models and was also looking at how to link data from its Structure Management System (SMS) to maintenance and its Equipment, Inventory, and Materials System (EIMS).

27. "A Stochastic Framework for Sustainable Infrastructure—Application to Pipes and Culverts," Jay N. Meegoda and Layek Abdel-Malek, *TRB 90th Annual Meeting Compendium of Papers*, Paper #11-2848, 2011.
Citation at http://trid.trb.org/view/1092706
From the abstract:

> To assist in this vein, a framework is developed for sustainable infrastructure system with a specific focus on prioritizing maintenance activities subject to operational and budgetary constraints. While the framework here considers culvert/pipe networks; its proposed methodology is portable to other infrastructures' types. The development process utilizes results from previous research on "Culvert Information Management System" (that dealt with identifying critical sections, inspection, prediction of service life based on the current condition states of the different culverts/pipes and assessing the present asset value) to provide the underpinning for building a stochastic optimization framework. Among the salient features of the framework is its proactive nature, which affords decision makers the means of conducting a comprehensive analysis to determine the optimal proactive schedule of the proper maintenance actions including inspection (that is whether to replace or rehabilitate the parts under consideration) and to prioritize them accordingly.

28. "Culvert Information Management System," Jay N. Meegoda, Thomas Juliano and Chi Tang, *Transportation Research Record 2108*, pages 3-12, 2009.
Citation at http://trid.trb.org/view/881509
From the abstract:

> A pilot scale culvert information management system (CIMS) was developed for the New Jersey Department of Transportation to comply with requirements stipulated by the Governmental Accounting Standards Board, GASB-34, and new federal stormwater regulations. The condition states of culverts are used to express the extent of their deterioration and survival probabilities. A financial analysis model was developed on the basis of the remaining value of culverts and the user cost of failures. Different rehabilitation options were discussed, and recommendations were made for deteriorated culverts on the basis of financial analysis. The pilot CIMS can analyze prescribed culvert information and make decisions to inspect, rehabilitate, or replace culverts or to do nothing at project and network levels. At the project level, this is achieved by comparing inspection, rehabilitation, or replacement costs with risks and costs

associated with failure. At the network level, the associated costs are optimized to meet annual maintenance budget allocations by prioritizing culverts needing inspection and rehabilitation or replacement. The CIMS has three major computer software components: databases, user interfaces, and functionality modules. Modules include inlet–outlet structures, culvert segments, culvert assessment, and optimization. Users are able to retrieve culvert and inlet–outlet structure physical and financial information and to generate reports vis-à-vis location, road, and milepost for condition state and assets needing immediate repair. The CIMS will also do the following operations: maintain an up-to-date inventory of eligible infrastructure assets; perform maintenance of eligible infrastructure assets for a given budget using a replicable basis of measurement and measurement scale; and summarize results, noting any factors that may influence trends in the information reported.

29. Culvert Information Management System—Demonstration Project, Jay N. Meegoda, Thomas M. Juliano and Chi Tang, New Jersey Department of Transportation, August 2009.
http://www.nj.gov/transportation/refdata/research/reports/FHWA-NJ-2009-017.pdf
This study developed a pilot scale CIMS. The report includes a section on relating condition states of culverts to remaining service life (pages 10-12) and a section on reliability analysis to determine the probability that a culvert will operate for a specific period of time without failure (pages 11-13). It also includes a section on the effect of rehabilitation on service life (pages 14-19). From the abstract:

> A framework for inspection and rehabilitation/replacement of corrugated steel culvert pipes (culverts) is developed, and this report will form the basis for the creation of a computerized CIMS. The justification of the development of the CIMS is based on recent GASB-34 requirements. The CIMS will serve as a vehicle for evaluating underground infrastructure assets, specifically culverts, and facilitate computing present worth and comparing present costs of preserving them. Benefits of the CIMS will include long-term savings that should accrue from adopting optimized preventive maintenance strategies. The Condition States of culverts are used to express the extent of their deterioration. Different rehabilitation options are discussed and recommendations are made for deteriorated culverts. These options that will be incorporated into the CIMS, use survival probabilities based on the condition state of culverts. The survival probabilities for being in Condition States 1, 2, 3 or 4 are computed based on minimal field data. However, the CIMS requires additional field data for culverts or laboratory tests that mimic field conditions to enhance this capability. The CIMS is capable of analyzing decisions to inspect, rehabilitate/replace or do nothing at both project and network levels. At the project level this is achieved by comparing inspection and/or rehabilitation/replacement costs with risks and costs associated with failure. At the network level, the associated costs are optimized to meet annual maintenance budget allocations by prioritizing culverts needing inspection and rehabilitation/replacement. The CIMS consists of three major computer software components: databases, user interfaces, and a data administration module. Secondary components include an inlet/outlet structures module and a culvert segments module. The inlet/outlet structures module will store all the storm water data such as the quality/quantity of water and the receiving and discharge watersheds. Users will be able to retrieve culvert and inlet/outlet information and generate reports via location and road/milepost for condition state and assets needing immediate repair. The CIMS will also do the following operations:
>
> - Maintain an up-to-date inventory of eligible infrastructure assets.
> - Perform condition assessments of eligible infrastructure assets at least every three years, using a replicable basis of measurement and measurement scale.
> - Summarize the results, noting any factors that may influence trends in the information reported.
> - Estimate yearly the annual amount needed to maintain and preserve the eligible infrastructure assets at or above a prescribed level.

Related Resource:

> **30. "Framework for Inspection, Maintenance, and Replacement of Corrugated Steel Culvert Pipes,"** Jay N. Meegoda, Thomas M. Juliano, Prasanna Ratnaweera and Layek Abdel-Malek, *Transportation Research Record 1911*, pages 22-30, 2005.
> Citation at http://trid.trb.org/view/767831
> From the abstract:
>
> > A framework for inspection, rehabilitation, and replacement of corrugated steel culvert pipes (CSCPs) is developed. It is expected to lead to developing a culvert information management system (CIMS), wherein justification and need are based on recent Governmental Accounting Standards Board (GASB) requirements. The CIMS will assist in evaluating infrastructure assets and facilitate comparing present costs of preserving infrastructure. Benefits include long-term savings from adopting optimized preventive maintenance strategies. CSCP condition states are used to express the extent of deterioration. Rehabilitation options and recommendations are given for deteriorated CSCPs. These options will be incorporated into the proposed CIMS, which uses survival probabilities based on the CSCP condition state during the previous year. Survival probabilities within Condition States 1, 2, and 3 are computed on the basis of corrosion research data. However, implementing the proposed CIMS requires field data for CSCPs or laboratory tests that mimic field conditions. The proposed CIMS can analyze decisions to inspect, rehabilitate and replace, or do nothing at both project and network levels. At the project level, inspection or rehabilitation and replacement costs are compared with failure risks and costs. At the network level, associated costs are optimized to meet the annual maintenance budget by prioritizing CSCPs needing inspection and rehabilitation and replacement. The proposed CIMS can also be used to estimate the required annual budgetary allocation for a stipulated planning horizon and to maintain or improve the aggregate condition state of the CSCP network or to maintain or improve the total highway CSCP network asset value, thereby meeting GASB 34 requirements. The optimum sequential path in the annual decision-making process may then be determined using a combination of operations research tools.

31. "Development of Framework for Roadway Culvert and Drainage Structure Inventory and Inspection," Mohammad Najafi and Deepak Bhattachar, *TRB 87th Annual Meeting Compendium of Papers*, Paper #08-1270, 2008.
Citation at http://trid.trb.org/view/847948
From the abstract:

> As many culverts reach the end of their design life, the states Departments of Transportation (DOTs) are in need of a model to track the condition of existing culverts and forecast their maintenance needs. Therefore, the main goals of this research are (1) to develop a framework for culvert inventory and inspection, (2) provide protocols and condition rating systems for culvert inventory and inspection, and (3) validate the developed framework by conducting field pilot studies. Performance scores for the culverts are calculated using an analytical hierarchy process (AHP). These scores are used to assess the magnitude of the deterioration, and assist in short- and long-term planning for rehabilitation and renewal. This study focuses on concrete, corrugated metal, and plastic culverts spanning less than or equal to 10 feet (3 meters). The developed model and procedure presented in this paper contribute to an effective culvert asset management strategy.

32. An Asset Management Approach for Drainage Infrastructure and Culverts, Mohammad Najafi, Sam Salem, Deepak Bhattachar, Baris Salman and Rahul Patil, Wisconsin Department of Transportation, June 2008.
http://wisdotresearch.wi.gov/wp-content/uploads/07-19-tpf-5036-f.pdf
The goal of this project was to develop field protocols and business rules for culvert inventory data management. The report includes the results of a pilot study to validate these processes and a survey of state DOTs. With 70 percent of agencies responding, 78 percent of respondents had no deterioration models to

predict the service lives of culverts, and 13 percent were developing models. Virginia had developed predictive models and Delaware used Pontis deterioration models.

33. Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures, Sam Salem, Mohammad Najafi, Baris Salman, Diego Calderon, Rahul Patil and Deepak Bhattachar, Wisconsin Department of Transportation, August 2008.
http://wisdotresearch.wi.gov/wp-content/uploads/08-30trenchlesstech-f.pdf
From the abstract:

> This study builds upon the findings of the previous research project and focuses on the application of trenchless technologies for inspection, construction, repair and renewal of culverts. A literature search, a survey of departments of transportation and a survey of technology providers have been conducted to identify and characterize trenchless technology methods used for buried pipes. The limitations of trenchless technologies in terms of applicability to culverts are investigated. Steps of establishing a comprehensive culvert asset management strategy are identified. Based upon the findings a decision support system is developed which will help the decision makers identify the optimum repair/renewal procedures as a function of the condition of the culvert.

34. Transportation Asset Management Case Studies: Culvert Management Systems: Alabama, Maryland, Minnesota, and Shelby County, Federal Highway Administration, 2007.
https://www.fhwa.dot.gov/infrastructure/asstmgmt/tamcs_cms.pdf
From page 5:

> This case study examines different types of culvert management systems (CMSs) used by State and county departments of transportation (DOTs). In order to determine the characteristics of a well-functioning CMS, the study focuses on the following aspects: inventory; inspection; management and documentation; and planning, budget, and decision-making methodology. This case study highlights the use of different management systems in Maryland, Minnesota, Alabama, and Shelby County (Alabama).

35. "Need for Culvert Asset Management," Joseph Perrin, Jr. and Rajesh Dwivedi, *Transportation Research Record 1957*, pages 8-15, 2006.
Citation at http://trid.trb.org/view/777721
From the abstract:

> As part of this report, all 50 U.S. state DOTs were sent a survey concerning culvert asset management issues. The resulting 28 responses identified that several states are working toward developing an inventory database and planning to implement an inspection program. Many are not yet considering applying asset management practices to their culvert infrastructure. Several agencies did identify failure as a primary reason for developing the inventory and inspection programs. Because culvert failures are often the motivation for agencies to respond, some recent failure examples are reviewed. Previous research recommended a national tracking of culvert failures to understand the risks and costs better. This paper builds on that idea and identifies the benefits of culvert asset management. These benefits include up-to-date inventory, reduced failures through regular inspection, reduced emergency repair costs and unplanned financial burden, better budget planning for repair and replacement, and long-term ability to identify actual life cycle and performance of various pipe materials.

36. "Management of Utah Highway Culverts," Jesse L. Beaver and Timothy J. McGrath, *Transportation Research Record 1904*, pages 113-123, 2005.
Citation at http://trid.trb.org/view/759649
From the abstract:

> The objective was to develop a system of qualitative and quantitative performance measures to assess both the long- and short-term behavior of highway culverts and to support the Utah DOT effort to modify and populate a computerized database designed to store culvert inspection data that can be used for statewide culvert asset management. Culvert management practices currently used by Utah DOT and other agencies

are described. A total of 272 culvert inspections conducted during this project showed the inventory to be aging but not generally in need of immediate maintenance. The Utah DOT database, developed to track culvert condition, is effective but could be improved. Improvements would streamline both culvert inspections and priority ranking of culvert repairs. The Federal Highway Administration system for rating culvert maintenance action was adopted, with a new proposed table for rating thermoplastic pipe. Culvert ratings were adjusted with an importance modifier that focused inspection and maintenance activity on critical culverts with higher consequence of failure. Critical culverts should be placed on a regular inspection schedule, whereas other culverts can be inspected during periodic roadway repaving or rehabilitation. Culvert inspection results will be added to the database to provide more insight eventually into culvert service life than is now possible.

37. Risk Assessment and Update of Inspection Procedures for Culverts, Gayle F. Mitchell, Teruhisa Masada and Shad M. Sargand, Ohio Department of Transportation, February 2005.
https://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Reports/2005/Hydraulics/14813FR.pdf
From the abstract:

A new culvert inspection rating system was developed by the Ohio Department of Transportation (ODOT) and described in their 2003 Culvert Inspection Manual. The Ohio Research Institute for Transportation and the Environment (ORITE) developed a proposed rating system and tested it and the ODOT system on 60 culverts in 8 of 12 ODOT Districts across the state: 25 concrete culverts, 25 metal culverts, and 10 thermoplastic pipe culverts. The ODOT rating system rates 16 items on a 0 to 9 point scale, while the proposed system considers 30-33 items on the same 0 to 9 point scale. This scale represents an improvement over the 4-point (good, fair, poor, critical) scale in use in Ohio since 1982. The inspection results indicate that concrete culverts have a service life limited to 70-80 years, and metal culverts have a service life limited to 60-65 years. A multivariable regression analysis of the inspection data found that for concrete culverts, age and pH were significant factors in both rating systems, while drainage flow abrasiveness was also a significant factor in the ODOT system. For the concrete culverts, the ODOT system had a higher adjusted R-squared value and detected more significant factors; the adjusted R-squared values were 0.45 and 0.39 for the ODOT and proposed systems, respectively. A larger sample size would have improved the level of accuracy and the number of significant factors. The multivariable analysis of the metal culvert inspection data found that the significant factors were age, rise, and culvert type. Abrasiveness, pH, and flow velocity were also significant factors in the proposed system. The proposed system had a higher adjusted R-squared value and detected more significant factors; the adjusted R-squared values were 0.75 and 0.43 for the proposed and ODOT systems, respectively. The sample size of thermoplastic culverts was too small to permit a meaningful statistical analysis. A risk assessment of the culverts was conducted based on the NCHRP Report 251 using an adjusted overall culvert rating. The adjusted ratings for the concrete culverts were between 2 and 6 in both systems, with one culvert requiring a highest priority of maintenance immediacy of action and two requiring high priority maintenance immediacies of action; the rest were rated between 4 (priority for the current season) and 6 (schedule work by the end of next season). Results for the metal culverts were similar, with the exception that only two culverts required a high level of maintenance immediacy of action. The adjusted ratings for the thermoplastic pipe culverts ranged from 6 (add to scheduled work by end of next season) to 9 (no repairs needed) in the ODOT system and from 5 (place in current season schedule at first reasonable opportunity) to 9 (no repairs needed) in the proposed system. A number of innovative culvert rehabilitation techniques were discussed, including slip-lining, cured-in-place pipe, invert replacement using concrete or gunite, filling voids, and repairing sleeves for localized problems.

38. "Simple Rating System for Identification of Failure-Critical Culverts and Small Structures,"
Katherine Wissink, Meghan McKee, Robert Houghtalen and Kevin Sutterer, *Transportation Research Record 1928*, pages 226-229, 2005.
Citation at http://trid.trb.org/view/778462
From the abstract:

> Although bridges are a highly visible and crucial part of the highway infrastructure, smaller structures typically classified as culverts exist in even greater numbers. Nearly invisible to the public, culverts are crucial components of highways. Failure of culverts can lead to flooding, roadway damage, interruption of traffic, and even fatal accidents. Several states have implemented successful culvert inspection programs, but others are only beginning to formalize their culvert inspection and maintenance. Even after periodic inspection programs are in place, planners need a tool for consistent guidance to identify structures most in need of attention. This paper reports on a simple rating system based on a new culvert inspection program recently implemented by the Indiana Department of Transportation. The rating system uses weighting factors that can be adjusted by the user to provide an overall rating of a culvert based on ratings of specific characteristics of a culvert. The tool can be used to provide a consistent comparison with other culverts across the state and to provide quality control of the inspectors' overall rating as entered into a database.