

Rating system for rural culvert crossing repair and maintenance
by Daniel W Baker

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University
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Abstract:
Many aspects of transportation infrastructure have benefited from the use of full-scale management systems in order to quantify the system's condition and useful life. While culvert management models have been tested in the past, none have proven functional. This project will develop a Rating System for Rural Culvert Crossing and Repair. The aspects of the overall project that this paper covers are the acquisition of the sample set data and the subsequent formation of the conditions rankings model. An initial list of culvert parameters, corresponding to specific failure mechanisms, was reduced due to the importance (as deemed by a multitude of experts in the field) and also the ease of field measurement. After a set of 33 parameters was established, data was collected throughout the state of Montana. The use of an ordered probit statistical model analyzed this sample set of data and further reduced the parameters to 9 final items. Measurement of these 9 parameters classifies the culvert into a 1 to 5 conditions ranking (5 being best condition and 1 worst). Merits of the project's results are two fold: first the explorations of the specific parameters that contribute to culvert condition are very valuable and secondly the numerical model should be applicable in a wide range of situations.

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MONTANA STATE UNIVERSITY – BOZEMAN
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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Many aspects of transportation infrastructure have benefited from the use of full-scale management systems in order to quantify the system's condition and useful life. While culvert management models have been tested in the past, none have proven functional. This project will develop a Rating System for Rural Culvert Crossing and Repair. The aspects of the overall project that this paper covers are the acquisition of the sample set data and the subsequent formation of the conditions rankings model. An initial list of culvert parameters, corresponding to specific failure mechanisms, was reduced due to the importance (as deemed by a multitude of experts in the field) and also the ease of field measurement. After a set of 33 parameters was established, data was collected throughout the state of Montana. The use of an ordered probit statistical model analyzed this sample set of data and further reduced the parameters to 9 final items. Measurement of these 9 parameters classifies the culvert into a 1 to 5 conditions ranking (5 being best condition and 1 worst). Merits of the project's results are two fold: first the explorations of the specific parameters that contribute to culvert condition are very valuable and secondly the numerical model should be applicable in a wide range of situations.

CHAPTER 1

INTRODUCTION

As our nation's infrastructure continues to expand and develop, accurate and advanced monitoring of transportation systems will become increasingly important. Comprehensive management plans can be, and are already used to quantify the condition and useful life of a system. Successful transportation infrastructure management systems have already been developed for road pavement and bridges.

One area that merits further development is the monitoring of culvert condition. Culverts are an important entity of the transportation network. They provide effective and inexpensive roadway passage over small streams, rivers and intermittent drainage paths. Additionally they are used for stock, human, and vehicle underpasses. As such, culverts are widely used by state, county, local, park, and forest service agencies.

From a transportation perspective, reactive as opposed to proactive measures related to culvert management can have significant safety and economic impacts. Should culvert failure result in closure of a roadway, delay costs associated with lost motorist time can quickly escalate. Even on low-volume rural roadways, road closures of any duration can result in significant delay and inconvenience to motorists who have to re-route long distances to reach their destination. Should culvert failure and subsequent roadway failure go undetected and uncorrected by responsible agencies, the risk of a serious crash is present. Crash-related costs range from $40,000 per moderate injury to $2,600,000 per fatality.[1] In addition to these medical-related crash costs; responsible agencies are often

subjected to liability-related costs associated with failure to provide a safe traveling environment. Reactive measures not only result in unnecessary safety- and liability-related spending, but also much higher culvert maintenance costs for the responsible agency.

Proactive culvert management would result in fewer, shorter and more managed (i.e., through traffic control) roadway closures, a reduced risk of safety and liability problems associated with culvert and subsequent roadway failure, reduced delay for the motoring public, and reduced culvert-related maintenance costs. The Montana Department of Transportation (MDT) alone utilizes over 35,000 road-crossing culverts, and another 18,000 side culverts as part of the state roadway system. Cost savings can be significant, MDT estimates spending $500,000 per year on culvert-related maintenance.[2]

Culvert crossing repair or replacement needs should incorporate the latest in hydraulic computation methods, consider environmental concerns, and access impact and cost factors. The need-based rating system described herein considers all pertinent failure mechanisms and the relative costs and transportation-related impacts of action or no-action.

Problem Description

Most decisions for culvert maintenance and repair are currently left up to the discretion of regional maintenance personnel. Services are provided on a need-basis only. Sometimes the need is not recognized until after a major failure has occurred and the entire culvert must be replaced. While culverts in areas of concentrated maintenance

attention will be well cared for, other, possibly critical, crossings will go unchecked. Well-timed maintenance can prevent catastrophic failure and the associated costs.

The Montana Department of Transportation (MDT) Maintenance and Planning Divisions are partners in this project. The MDT Planning Division is currently in the process of developing an all-encompassing Performance Programming Process (PPP) that evaluates all project nominations. One of the criteria that will be used to determine whether a project moves forward is the culvert condition if a culvert is involved. The MDT Maintenance Division is currently developing an Inventory Condition and Assessment System (ICAS) that will allow for a functional and qualitative evaluation of roadway infrastructure assets. The proposed culvert rating system will support the ICAS by providing the necessary engineering considerations. Currently, the MDT Maintenance Division performs an annual inspection of most culverts, but has no formal process for prioritizing funding for repair and/or replacement. As a result, the MDT Maintenance Division has been historically reactionary in nature, responding when there is some sort of emergency.

The development of the systematic rating procedure described here would directly support MDT's Maintenance Division efforts to be more proactive rather than reactive and consequently result in better management of maintenance resources and personnel. Further, the proposed effort would support the larger effort of MDT project prioritization and selection by directly feeding critical data to a larger multi-criteria program (i.e. the PPP). MDT's interest level in the proposed culvert rating system is high and personnel

from MDT's Planning and Maintenance Division have committed staff time to ensure that the project is successful and will be fully integrated with their efforts.

Background

Rural roadways in the arid west often use culverts as an inexpensive and effective alternative to elevated bridge decks. The performance of a given culvert is dependent on both regional hydrology and structural considerations. Aging culverts with minor mechanical damage, sedimentation or collected debris can become safety hazards to rural motorists as a result of reduced culvert flow capacity. Reduced culvert flow capacity means that failure can occur even if weather conditions are within the realm of those considered by the design engineers. Many of the public-lands access roads that promote rural tourism use culverts instead of bridges due to the reduced replacement cost if failure occurs. This cost, and the associated safety risks, could be markedly reduced by avoiding failure through the use of a comprehensive maintenance and replacement assessment program.

Bridges vs. Culverts

To convey water beneath an intersecting roadway, designers have traditionally had two options: bridges or culverts. Bridges have several distinct advantages. First, bridges allow the transmission of large flows of water beneath roadways. In comparison to culverts, bridges are quite advantageous in respect to preserving the natural condition of the channel, reducing channel constrictions and preserving the natural stream bed conditions. They also exhibit a longer service life when flow is continuous and carries

significant erosive bed load. Additionally, they tend to be more hospitable for fish passage and are more accommodating to diverse flows where backwater effects are undesirable during extreme flows. While bridges perform well hydraulically, their initial construction cost far exceeds that of a culvert. Due to these economic concerns, culverts are substituted where possible. Culverts, greater than 20 feet in diameter, are considered bridges as part of the Bridge Inspection Program by the Federal Highway Administration (FHWA)[3]. Smaller culverts are still lacking such systematic scrutiny.

Many culverts experience intermittent flow and infrequently operate at the design flow rate. In order to guarantee the ease and safety of culvert inspection, most evaluations will occur at lower flow rates. Inspections must still anticipate the consequences of high flows on the structure and surroundings. Consequences of high flow events will need to be recognized through clues around the culvert site and the understanding of culvert hydraulics.

Report Purpose and Contents

The purpose of this project is to develop a rating system that evaluates the condition and effectiveness of existing culverts and considers the transportation-related impacts of repair or replacement against the transportation-related impacts of no action. The rating system will first provide guidelines for selecting high priority culverts based on visual inspection, service records, or other qualitative information. After data has been compiled, the rating system will use a proven model to predict a condition with respect to biologic or environmental goals, traffic capacity records, and other qualitative indicators

to establish a weighted rank of the culverts in terms of repair and maintenance needs and the associated benefits of repair or maintenance. The main objective of this project is to develop a user-friendly, yet comprehensive culvert rating system.

The benefits of this project will be realized at several levels:

- Maintenance – Maintenance personnel will get an immediate feedback when compiling the raw inspection data, as the model will indicate which culverts are a priority to repair, allowing better use of manpower and financial resources at hand. The rating system could be used to develop a thorough monitoring of every culvert under their jurisdiction.
- Planning – With transportation planning looking further into the future, planners need a tool to forecast the condition of road structures at pivotal points in the system's development. In this way, culvert improvements may be executed in synchronization with road improvements, so that all aspects of a highway system may be improved in a timely manner with less disruption and cost to the public.
- Economic – In order to receive proper funding from their controlling legislative bodies, departments of transportation need more advanced and structured forecasts of maintenance and replacement costs. While this project will not provide direct useful life or cost/benefit analysis, the data collected for this project may be used in the future to develop such models.

This paper begins by discussing of the hydraulic properties of culverts and the failure mechanisms that render them ineffective. Chapter 2 summarizes recent work done similar to this project. Then in Chapter 3, the methodology of this project is discussed,

including background development, data acquisition, and model evolution. Chapters 4 and 5 describe the findings of this investigation in detail and provide a synopsis of the project's results and conclusions.

Project Funding

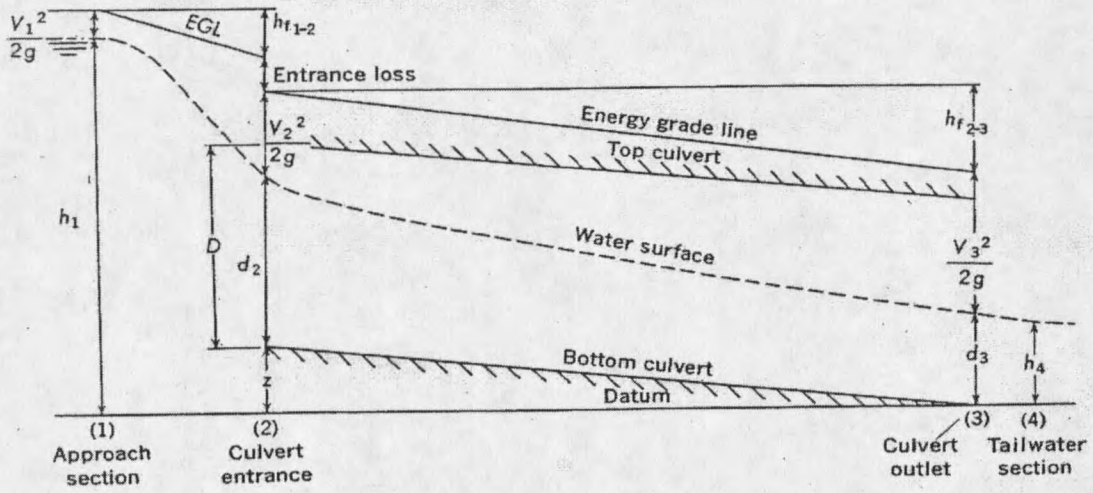
The previous two federal transportation funding bills, Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and the Transportation Equity Act for the 21st Century (TEA-21), have authorized substantial finances to establish regional University Transportation Centers in order to facilitate transportation education and research. Montana State University, through the Western Transportation Institute, was designated a federally funded University Transportation Center in 1998. Since that time grants have become available for research opportunities.

Hydraulic Properties

Many of the advantages, and also the limitations, of the hydraulic characteristics of culverts need to be explained in further detail in order to understand why specific failure criteria or degradations would have such a significant impact.

Culverts can convey large flow rates, but in some cases this requires that the inlet be inundated. Culverts in a series can have the effect of staging; the water is stored intermittently, where bridges must be designed to pass the maximum flow at any one time.[4]

Figure 1. Culvert Cross Sectional Diagram



Except during peak flows, flow approaching the culvert is often tranquil and moderately uniform. Within the culvert the flow may be tranquil, critical, rapidly varying, or flow full under pressure.[5] Hence, the standard approach to solve the hydraulics problem is to assume one of the following two conditions:

Inlet Control – If the culvert barrel is capable of conveying more flow than the inlet will accept, it falls under inlet control. If the inlet is not inundated, the critical depth occurs at or near this location, and the flow regime immediately downstream is supercritical. The upstream water surface elevation and the inlet geometry represent the major flow controls.[6] The calculation of inlet flow conditions computes the upstream headwater depth using energy balance computations that consider the predominant losses due to the culvert barrel friction as well as the minor entrance and exit losses.[5]

Outlet Control – Converse to inlet control, the barrel cannot convey as much flow as the inlet will allow. Hence either subcritical or pressure flow exists in the culvert barrel under these conditions. All hydraulic characteristics, including tailwater elevation, barrel

slope, roughness, and length play a role in determining this culvert's capacity.[5] Calculations for outlet control compute the upstream headwater depth using energy balance computations that consider the predominant losses due to the culvert barrel friction as well as the minor entrance and exit losses.[6]

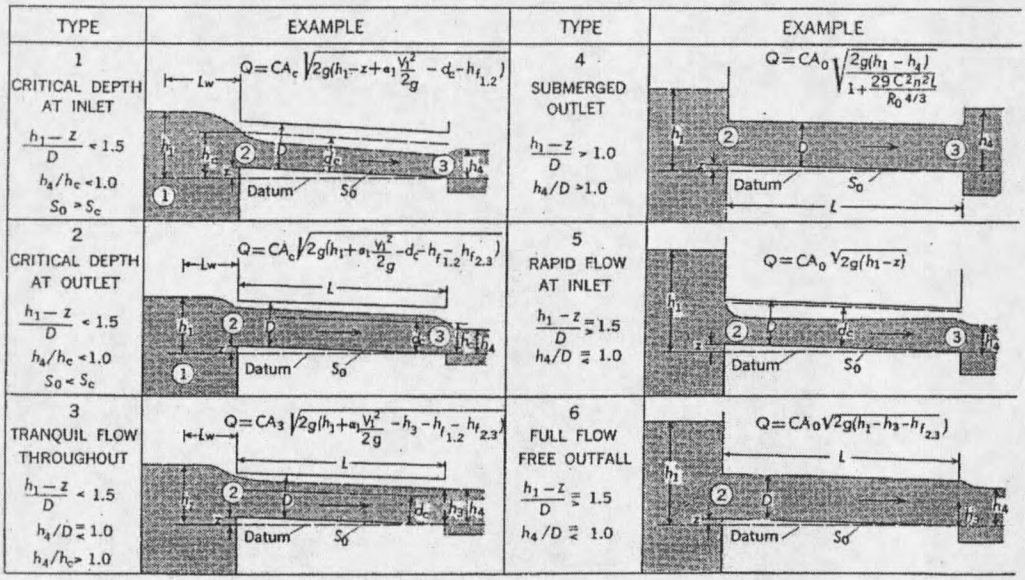
Research by the National Bureau of Standards (NBS), sponsored and supported by the Federal Highway Administration (FHWA), formerly the Bureau of Public roads (BPR), began in the early 1950's and resulted in a series of reports. These reports provided a comprehensive analysis of culvert hydraulics under various flow conditions.[6] One of the most exhaustive studies into culvert hydraulics was compiled by G. L. Bodhaine in 1967 for the United States Geological Survey (USGS). Bodhaine attempted to categorize all culvert flow into six different flow types based on the location of the control section and the relative heights of the headwater and tailwater elevations.[5]

These six types can be subdivided into six classifications as shown in Figure 2. If the inlet and outlet are not submerged, only flow types 1, 2, and 3 are possible. If both the inlet and outlet are submerged, only type 4 flow possible. If the inlet is submerged with the outlet not submerged, the remaining flow types 5 and 6 are possible. General descriptions and controlling sections of the six numbered flow conditions are:

- Type 1 – Supercritical flow through culvert barrel with flow dropping to critical at inlet.
- Type 2 – Subcritical flow the length of the barrel with the flow dropping through critical at the outlet.
- Type 3 – Tranquil flow throughout culvert barrel, flow controlled by barrel losses.

- Type 4 – Submerged outlet with full pipe flow.
- Type 5 – Submerged inlet and orifice controlled pipe flow.
- Type 6- Full pipe flow with free outfall at outlet.

Figure 2. Bodhaine's Classification of Culvert Flow

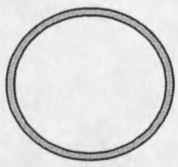
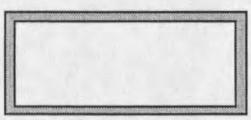
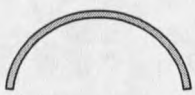


Culverts typically act to restrict the flow area of the waterway. This restriction increases the flow velocities within the barrel in comparison to the channel itself. Higher flow velocities tend to keep fine sediments from being deposited within the barrel, but these same high velocities and their increased bed load capacity can also cause problems with streambed scour and bank erosion at the outlet.[6] At high flows, waterways undergo many changes, mainly due to the higher velocity of the water, enabling the fluid to transport a greater volume and dimension of bed load.[7]

Culvert Shape Characteristics

Selection of culvert shape will depend on the characteristics desired of the flow through the culvert, and the physical limitations of the surrounding environment.

Table 1. Culvert Shape Descriptions

Culvert Shape	Description
Circular 	• Circular culverts are the most common due to their low cost, ease of installation, and high strength. • They are advantageous for fish passage as low flows result greater depth than other culvert shapes.
Pipe Arch 	• Pipe arch culverts are used in cases with fill height limitations. • Pipe arch culverts are not as structurally strong as circular culverts, and typically are more expensive for equivalent hydraulic capacity.
Rectangular or Box 	• Rectangular culverts are the most efficient at reducing headwater elevations for a given cross sectional area, but are detrimental for fish passage. • Most box culverts are made of reinforced concrete and are more expensive than either circular or arch culverts.
Arch (open bottom) 	• Arch culverts most closely simulate bridges, maintaining a natural bottom condition. • Arch culverts still restrict the natural channel, and therefore are subject to scour. • Footings must be located below scour depths.

Culvert Hydraulic Analysis Software

Many software developers have attempted to simplify the complexities of culvert hydraulics. All culvert analysis packages are working on the same physical flow phenomena, hydraulics, and principals, but each employ a variety of basic assumptions and simplifications in order to accomplish their task of a numerical solution.

CulvertMaster – Produced by Haestad Methods in order to explicitly solve culvert problems, CulvertMaster has a very easy to use interface with many beneficial features. CulvertMaster will analyze simple culverts or complex embankment cross drain systems.

CulvertMaster contains a 'Quick Culvert Calculator', which simply models water flow from the inlet to the outlet of a culvert. Additionally, it can perform an exhaustive 'Analysis' for in-place culverts including watershed calculations of flow data and tail water calculation with consideration to the downstream channel. Finally the 'Design' option of CulvertMaster allows input of basic site and roadway data that will apply for a specific culvert crossing. Various design trials can consider the same watershed and tailwater calculations as the 'Analysis' mode, with the addition of local grades and headwater limitations.[8]

The underlying mathematics for CulvertMaster are based on the publication Hydraulic Design of Highway Culverts (HDS 5) by the FHWA. While the assumptions contained in HDS 5 were found to cover most cases, it neglected certain flow conditions, namely full-pressurized pipe flow (Case 6 by Bodhaine's classification).

HEC RAS – The River Analysis System (RAS) produced by the U.S. Army Corps of Engineers Hydrologic Engineering Center in Davis, California is an open channel flow profile software package that includes analysis of not only culverts, but also bridge piers, weirs, and spillways. This program is designed to replace the HEC-2 backwater program and will analyze networks of channels, natural or manmade, and compute water surface profiles using steady, one-dimensional flow hydraulics. HEC RAS is specifically designed to compute backwater profiles of river systems; culvert evaluation is cumbersome, but accurate. In order for HEC RAS to compute water profiles including culverts, specific techniques must be applied to account for the ineffective flow areas on either end of the culvert.

An Excel Template for Generating Rating Curves for Corrugated Metal Pipe Culverts

The previously mentioned culvert analysis programs can be expensive to obtain, and may require extensive training to operate. Therefore a simple-to- use and freely distributed spreadsheet was developed concurrently with this project by Dr. Joel Cahoon. This template calculates all six of Bodhaine's flow cases for a restricted set of culvert shapes and materials. A further explanation of this template and information on how the program can be obtained is in Appendix B of this document.

Failure Criteria

Culverts share a multifaceted relationship with their surrounding environment. To better understand this relationship, one must consider all failure criteria that may lead to culvert maintenance or replacement. Establishing failure criteria for any engineered system is mandatory to determine the system's potential for success. While failure may occur in a multitude of ways, the initial failure will be the controlling mechanism. In order for the culvert to be effective, it must work in harmony with the drainage it is transmitting, the overlying roadway and the channel that it adjoins.

Nearly as important as the establishment of the predominant failure mechanism is the development of threshold values for the degree of failure within each mechanism. If periodic maintenance is required to restore full flow capacity to the culvert, but water does not interfere with road users, it is of moderate concern. But if the culvert fails either structurally or hydraulically to the point that road users must detour the crossing, the situation is considerably more critical. The following sections will outline the likely

ways a culvert may fail. The failure model developed here will consider all pertinent failure mechanisms, with the final model including only those factors shown to directly effect the overall culvert condition. Additional complexity is introduced by the interaction between failure mechanisms; the development of a minor flaw may lead directly to the catastrophic failure of another.

Piping

Runoff water is very efficient; it will find the least restrictive pathway to flow downstream from its source. When culverts are inadequate and water is allowed to flow through the fill surrounding the culvert barrel; piping results. The two primary causes of piping are deficient end treatments and poorly compacted fill immediately around the culvert. Inadequate end treatments allow the infiltration of water around the culvert barrel, while the improper compaction of fill around the culvert allows fill material to be displaced and removed by the flowing water. Piping leads to instability of the roadbed above the culvert. This results in damage to the road surface, and also deformation of the culvert itself due to differential pressures caused by material voids around the culvert-soil interface.

Sedimentation and Debris Collection

The total flow in a culvert is equal to the velocity multiplied by the flow cross sectional area. Fine sedimentation in the culvert barrel can result from backwater pool effects at the downstream end of a culvert. Subsequent flow events deposit additional layers of sediment in the invert of the culvert, eventually blocking the majority of the

cross section. Many times these backwater pools are due to the culvert being installed too low in the cross section. Flushing of this fine sediment can be accomplished with flow velocities as low as 2 to 3 feet per second.[9] Coarse cobble can collect in the culvert barrel due to natural bed loading.

Debris collection may occur at the inlet to the culvert or within the culvert barrel. It is usually caused by large debris attempting to pass through the barrel, material getting caught on a mechanically damaged inlet, or material becoming wedged inside the barrel. Most problems with debris collection do not merit major repair or replacement, simply the removal of the debris. But backwater effects of debris can trigger other failures.

Another factor that may contribute to debris collection is vegetation growth at either the inlet or outlet of the barrel. Typically, flows of 2.5 feet per second will limit vegetation growth within the channel.[9]

Corrosion

Corrosion can attack culverts from the interior or exterior. Corrosive water flowing in the culvert can slowly degrade the interior surface of the culvert material. In order to limit this potential damage, protective coatings can be used on culvert interiors. In order to alleviate both types of corrosion, it is important to select the least reactive material for the culvert, and in extreme cases additional coatings and/or treatments may be merited.

New types of corrosion resistant culverts have been developed, but to date are in limited use in most areas. The predominant type of corrosion resistant culverts is constructed of high-density polyethylene (HDPE). HDPE is the most chemically inert of

all commodity plastic raw materials and has become the standard for chemically active acidic or alkaline site conditions.[10]

Abrasion

Abrasion is caused by sediment bed load moving within the culvert, slowly wearing away at the invert. The widespread use of galvanized corrugated metal pipe (CMP), makes abrasion of particular concern because the zinc coating, commonly known as galvanization, is worn away. The removal of this protective coating in turn exposes easily corroded bare steel. Abrasion is accelerated in streams that carry abundant bed load, and the subsequent corrosion in areas with highly corrosive water. Due to higher volumes and sizes of sediment transported, culverts in mountainous areas are typically suspect to greater degrees of abrasion damage. The Montana Department of Transportation has found that abrasion and corrosion are some of the leading causes of required maintenance or catastrophic culvert failure.[11]

Physical Damage

Physical damage to the culvert may occur from the exposed ends of the culvert being damaged by cars leaving the roadway or improper road and ditch maintenance activities. Damage severity can be limited to bent or broken outlet or inlet or as major as complete collapse of the damaged sections. If the disrepair may be corrected onsite, no major replacement is merited.

As discussed in the Hydraulic Properties section, the hydraulic capacity of culverts can be a direct function of its inlet or outlet. Thus minor physical damage can

significantly reduce the hydraulic efficiency of each culvert. Hydraulic tests have shown that even the location across a rib where corrugated pipes are cut can make a significant difference in hydraulic capacity, most of all when submerged.

Channel and Drainage Basin Alteration

Runoff calculations are directly based on the ground cover of the area they drain. If land use patterns are altered in these drainage areas, runoff volumes can deviate drastically. Examples of watershed changes include deforestation, subdivision development, or changes in agricultural practices. While increased water quantity is not directly related to the culvert failing, forcing a culvert to transmit greater volumes than its design capacity can trigger other failure mechanisms.

Fish Passage

One of the more recent, and somewhat debated, challenges to culverts is fish passage. As culverts have replaced bridges on many constant flowing waterways, and fish habitat preservation and rehabilitation have become major priorities, the ability and ease of a fish to pass through a culvert is quite important. Unfortunately the optimum hydraulic design and the design optimizing fish passage do not always coincide. Optimum hydraulic efficiency is obtained using a culvert with smooth interior walls, and design for the culvert to flow full with high flow velocities. Locations of optimum conditions for fish passage are low flow velocities created by high roughness and debris deposits.

Culverts limit fish passage in a variety of ways. The major factor is the increased flow velocity through culverts, in comparison with the disturbed channel bed. While fish

may be able to reach these high speeds for limited amounts of time (darting speed) they have difficulty in maintaining high rates of velocity for long periods. Thus some culverts may require either natural or man-made obstructions create backwaters and rest areas for migrating fish.[12] However, these obstructions within the culvert barrel will have a negative effect on hydraulic capacity, and the lower flow velocities may create additional problems with sedimentation.

Another factor that can inhibit fish passage upstream is the perching of the outlet of the culvert barrel. A perched outlet is a case where flow from the culvert outlet free falls into the downstream channel, this can be attributed to scour from the culvert itself, or initial improper installation. Perched outlets prevent fish with inadequate jumping abilities to enter culverts and progress upstream. A middle ground needs to be negotiated to not only allow natural passage of fish, but also efficient conveyance of water through the culverts.

Approach Roadway Condition

In situations where the culvert condition is not inspected regularly, damage to the surface of the overlying road may be the first indication of serious problems with the culvert below. Failures along a small diameter culvert will be difficult to see from the inlet or outlet, and damage to the road surface may provide the only means of warning. Common defects would include sagging and increased transverse cracking of the road surface. Settlement of the guardrail or sloughing of the road shoulder would also be clear indicators of problems.

Erosion or Failure of Side Slope

Erosion of the side slopes at either the upstream or downstream ends of the culvert can be attributed to inadequate armoring and can be an indicator of other failure types. Armoring can come in the form of vegetation and/or larger sized aggregate. If armoring is not feasible, the aspect angle of the side slopes must be decreased in order to limit runoff velocities. Erosion of the downstream embankment may be due to overtopping and/or piping.

Settlement and Joint Separation

Flow characteristics of culverts are sensitive to minor changes in slope and thus settlement can alter hydraulic performance and additionally can lead to other problems. Frequently, settlement of the culvert will lead to damage of the overlying roadway. Settlement can also be the predecessor to other types of failure such as sedimentation, joint separation, and scour issues at the outlet end.

Joint separation occurs when the junctions between prefabricated culvert sections are disrupted. This can lead to either infiltration, or more frequently exfiltration, of flow from the culvert. Introducing moisture to the base and sub-base of a roadbed can have detrimental effects such as expansion of soil or flushing of fine particles leading to settlement of the remaining coarse material. Typically joint separation is difficult to assess, especially in small diameter culverts of long length where direct determination will be nearly impossible and observation of secondary factors such as roadway or side slope damage, or differences in inflow and outflow of the culvert must be observed.

Buoyancy Failure

During high flow, when either the inlet or outlet are submerged, but the barrel of the culvert does not flow full, the culvert may experience problems with buoyancy uplift. Projecting inlets on corrugated metal pipe of large diameter (greater than 5 feet) are particularly susceptible to uplift bending. While this type of failure only occurs in extreme cases, it is an important design issue for larger diameter culverts or culverts with steep slopes. Smaller culverts are less susceptible as the ratio between the area within the culvert (defining the potential buoyancy force) to the weight of the fill above the culvert is much less. Physical damage to culvert inlet may accentuate this problem. Proper inlet design can reduce the size of the culvert needed and reduce the chance of uplift by allowing the pipe to flow full.[13]

Overtopping

When the backwater of a culvert increases beyond the height of roadbed, water will flow over the road and may result in erosion of the road surface or shoulders. The amount of embankment erosion caused by overtopping depends on the depth of the overtopping, the tailwater elevation, the duration of the event, and the soil and surfacing types. Overtopping can be the result of inadequate sizing or design of a culvert system. Culverts on minor roads may be designed to overtop during extreme flows, limiting the size and related expense of the culvert installed.

Structural Collapse of Barrel

Culvert barrels are not only a hydraulic structure, but are also a structural part of the roadbed and must support the weight of the above roadway and traffic. Circular culverts

depend on the compressive strength of their shape for strength, and any minor deformations should be considered catastrophic, as further damage will likely occur. Degradation of the culvert material due to abrasion or corrosion contribute to a decrease in culvert strength.

Remedial Measures to Failure Criteria

Failure of culverts can be caused by three broad categories: age, improper design or installation, and acts of nature.

Of the three causes, age is the one that engineers can do the least about, but it is the most predictable. Various federal and state transportation departments have developed useful life predictors for culverts (mainly dealing with corrosivity) and associated factors of safety. Adequate installation and maintenance records are of the utmost importance in monitoring culvert age.

Improper design and installation are human caused errors; the first due to lack of judgment or information during the engineering phase, and the second due to unskilled or improper work during the construction phase. Both can be prevented with proper training and attention to detail.

Acts of nature include storms, runoff patterns, and characteristics of the basin which the culverts are installed to drain. They cannot be altered, but the accuracy of runoff volumes and flood sequencing can lead to a proper design.

Problems with culvert installations prior to the 1960's related to embankment scouring, buoyancy, and piping led MDT to take action on its new installations. In order

to mitigate piping and buoyancy problems, cut off walls were used. Additionally, the use of concrete edge protection on inlets and riprap on embankments is used to reduce the effect of scour and collapse of inlets due to negative pressure in pipe entrance.[11]

CHAPTER 2

STATE OF THE PRACTICE REVIEW

Review of current literature indicates that little information has been developed and reported relating to culvert management or ranking systems. The first item in this review is the existing FHWA program to analyze large culvert condition. Next, numerical models that have been developed to predict useful life results dependent predominately on corrosion resistance are discussed. Additionally, the culvert management system developed herein will have similar attributes to existing bridge and pavement management systems, and therefore a brief discussion of bridge and pavement management systems is presented. Finally, a monetary based culvert ranking system is summarized.

FHWA Culvert Inspection Manual

Improvements in structural capacity and cost comparison to bridges have increased the use of large diameter culverts in recent years. In order to more accurately monitor these structures, the Federal Highway Administration (FHWA) decided to organize an inspection procedure and supporting manual for these structures. The definition of culverts in the "Bridge Inspectors Training Manual 70", is "...structures over 20 feet in span parallel to the roadway are usually called bridges, and structures less than 20 feet in span are called culverts even though they support traffic loads directly."[3]

Thus "culverts" over 20 feet in span needed special attention. In 1986 the FHWA developed a "Culvert Inspection Manual" to address these large culverts as a supplement to the standard "Bridge Inspectors Manual." As part of the FHWA Bridge Inspection Program, large-span culverts are included on a biannual inspection cycle. This still leaves the smaller culverts without mandatory inspection.

Some qualities of the FHWA's system include well-organized maintenance rating scale and a thorough inspection of every aspect of culvert failure mechanisms. The inspection includes multiple phases:

(1) A review of available information, including previous reports and plans, prior to the fieldwork,

(2) Observation of the overall condition of the culvert and its surroundings,

(3) An analysis of the approach roadway and embankment,

(4) The waterway is inspected, concentrating on location problems, sedimentation, scour, and waterway accuracy,

(5) The culvert end treatments are analyzed for damage and condition,

(6) And the culvert barrel itself is inspected.

While this type of exhaustive analysis would yield accurate results for smaller culverts as well, it is not economically feasible to put this amount of time and work into every culvert in a large scale transportation system. A system which does not sacrifice this accuracy, but which can be accomplished more quickly and efficiently is desired.

The specifics of the barrel inspection vary according to the culvert material. Table 2 contains a summary of the ratings that the system assigns.

Table 2. FHWA Culvert Maintenance Inspection Rating Scale

	Immediacy of Action	Course of Action
9	No repairs needed.	Note in inspection report only.
8	No repairs needed. List specific items for special inspection during next regular inspection.	
7	No immediate plans for repair. Examine possibility of increased level of inspection.	
6	By end of next season - add to scheduled work.	
5	Place in current schedule - current season - first priority opportunity.	Special notification to superior is warranted.
4	Priority - current season - review work plan for relative priority - adjust schedule if possible.	
3	High priority - current season as soon as can be scheduled.	
2	Highest priority - discontinue other work if required - emergency basis or emergency subsidiary actions if needed) post, one lane traffic, no trucks, reduced speed, etc.)	Notify superiors verbally as soon as possible and confirm in writing.
1	Emergency actions required - reroute traffic and close.	
0	Facility is closed for repairs.	

Missouri Department of Transportation Culvert Research

Since the early 1930's the Missouri Department of Transportation (MoDOT) has evaluated the durability and performance of galvanized corrugated steel pipe (CSP) and reinforced concrete pipe (RCP). The studies revealed a service life of about 50 years for CSP and nearly 100 years for RCP.

A report published in 1991 reinforced these service life estimates.[14] It additionally concluded that attempts to relate service life to measurable environmental parameters such as pH, abrasion, soil resistivity, chemical properties of the runoff, and watershed characteristics proved unsuccessful. Results showed that no single or combination of parameters would accurately predict service life in all areas of the state.

Currently, Missouri has committed to a biannual inspection of 230 culverts located in seventy-one counties across the state. This program, instituted in 1991, is part of the development of an inventory database established in 1987 to track the type, location, and service life of culverts installed.[14] The study began by selecting a statistically valid sample varying across geography, age, and culvert material. Global positioning technology is being used to accurately locate the culverts, and summary sheets adopted from the "FHWA Culvert Inspection Manual" are used to record culvert condition. They have expanded this research to include high density polyethylene (HDPE) pipes as well.[15]

Montana Department of Transportation Culvert Useful Life Calculator

Montana currently employs a useful life calculator with respect to culvert corrosion on all new construction and rehabilitation projects. This spreadsheet requires inputs of a culvert's age, material and thickness and the soil parameters of pH level, conductivity, resistivity, and percentage of sulfates. It then will analyze the useful life for various materials and recommended coatings and/or treatments. While this system does a thorough job with respect to corrosion, it ignores the remainder of failure criteria.

California Culvert Maintenance-Free Service Design Estimator

Similar to the Montana Useful Life Calculator, California employs its own version of a functional life estimator. This DOS based program considers not only the corrosive potential of the soil and water (using the parameters of both water and soil pH and resistivity), but also takes into account channel flow conditions. The program then

calculates estimated service life for various coating treatments and makes recommendations for material usage.[16] In order to account for constant flow conditions, this program allows the user to reduce the life of the invert coating by one half if the channel is constantly flowing, due to consistent contact with water and abrasion. The effects of abrasion are factored in by allowing the user to select estimates for flow velocities.

FHWA Bridge Management System

Studies have shown that more than 40 percent of all the 575,000 highway bridges in the United States are functionally obsolete or structurally deficient.[17] In order to proactively monitor all bridges, the Federal Highway Administration began developing a bridge management system over the last 25 to 30 years. This management system makes the most efficient use of the typically meager funds allotted for bridge preservation and rehabilitation.

Upon formulation of the National Bridge Inspection Standards (NBIS), every bridge on a public road must be inspected every two years, and data from these inspections must be inventoried and the critical bridge inventory updated. In order to logically analyze and use these vast amounts of data, cooperating groups under the direction of the FHWA have developed clear definitions of key bridge management principles and objectives. The most recent bridge management system implemented is the Pontis computer program. It incorporates dynamic, probabilistic models and a detailed bridge database for predicting maintenance, improvement, and replacement needs. In addition, the program

will recommend optimal policies and schedule projects within budget and policy constraints. Ponits provides a more detailed description of bridge conditions and its models are designed to operate on groups of bridges or whole inventories, rather than on individual structures.[17]

One challenge to the gathering of accurate information is doing so in a nondestructive manner while still detecting flaws such as delamination and fatigue cracking of the surfacing and cracking and fatigue of the bridge structure. No matter how complex or sophisticated the programs and algorithms are that perform the analysis and recommendations, they are only as good as the data that was used to formulate them. In order to improve data quality, FHWA is partnering in efforts to use advanced data collection techniques. A wide variety of detection methods are currently being used, and more advanced methods are under development.[17]

Originally data for the management system was obtained through field inspections through the National Bridge Inspection program. But recent programs have integrated this data with climate, hydraulic, hydrologic, geotechnical, and earthquake data to formulate advanced studies between bridge conditions and external environmental conditions.[18]

Future culvert management systems should emulate the thorough nature and use of advanced modeling techniques employed in the FHWA's Bridge Management System.

FHWA Pavement Management System

Pavements make up the largest capital investment in any modern highway system. Maintaining and operating pavements on a large highway system typically involves exceedingly complex decisions of when and what type of maintenance is required. Traditional methods left these critical decisions up to road supervisors, who would make these decisions based on their individual experience and knowledge. Rarely are there enough funds to complete restoration in all instances, and the timing of maintenance in high traffic areas are severely restricted.

Pavement management systems consist of three components: (1) a system to regularly collect highway condition data, (2) a computer database to sort and store the collected data and (3) an analysis program to evaluate repair or preservation strategies and suggest cost-effective projects to maintain highway conditions.[19] Methods of data collection range from driving surveys to the use of elaborate testing vehicles that measure smoothness, skid resistance, faulting, and cracking in the road surface. Data from identical length segments is then input into a database and used for comparison purposes. This database and subsequent analysis are usually set up using commercially available software featuring many custom features according to the need of the agency.

The analysis portion of the pavement management system attempts to predict how long a pavement segment will last with specified repairs, taking into account traffic loads, climate and other factors. The basis of the analysis is twofold, based on the collective expertise of road experts, and the historical costs incurred for repairs or reconstruction. Overall, the intent of the analysis is to identify the most cost-effective ways to maintain a

highway system in satisfactory condition. Early challenges found in developing pavement management systems are as follows:

(1) Costly Maintenance Practices – State, Federal, and local governments invest more money in highway maintenance than for any other purpose. While the actual cost for these repairs is large, strong evidence suggests some of the high costs originate from inappropriate or poorly timed maintenance activities.

(2) Preservation vs. Construction – After years of collecting pavement data, it became evident that it was far more economical to preserve roads than to delay repairs and reconstruct roads. Studies further showed that as traffic levels increase, the costs of delaying repair work increased greatly.

(3) Data Collection Problems – Data collection by observation was very difficult and was often not objective. Data collection on the large highway systems usually required several observers to collect data and this led to inconsistencies. These factors led to the development of vehicles that mechanically measure road conditions.

(4) Computer Evolution – Computers, even 15 years ago, were excessively burdened with the task of working through the large amount of data in pavement management programs, but the evolution of power in today's desktop computers has made this analysis multiple alternatives rapidly.

Most current highway system administrations have incorporated pavement management systems into their operating plans. Agencies report that the systems are worthwhile, but several data collection cycles are required before significant cost savings in operation and maintenance are realized.

Micro-Computer Based Culvert Rating System

The Transportation Research Record published a culvert ranking model based on economic factors in 1991. This model was developed with goals similar to those herein- ranking culverts based on a limited set of parameters to forecast culvert condition.

The parameters included in this model were:

- posted weight,
- average daily traffic (ADT),
- relative width,
- detour length,
- flood detour length,
- flood days per year,
- average cost per day per flood and
- maintenance costs per year.[20]

A level of service (LOS) approach was adopted for this model. Goals for the LOS of each culvert parameter were established in accordance with highway functional classification, traffic volume, and other factors. When a culvert parameter failed to meet its service goal, a deficiency occurred. Four priority ranking formulas were developed analyzing load capacity, hydraulic capacity, width deficiency, and maintenance costs. The priority ranking formulas were then weighted for importance in order to collectively return a condition rating.[20]

This system has several important qualities. First, it is based on the universal perspective of money. All people can compare monetary results, and deduce the same

conclusion. It also takes into account the value to the motorist if they are forced to detour the crossing during times of failure. While this system attempted to encompass all problems dealing with culvert deterioration, it fell short in several areas. In order to establish the basis of economic loss, some values were estimated, such as the average cost per day of flooding. Additionally, factors such as flood days per year are difficult, if not impossible to accurately detect. They would require constant monitoring of every site. Next, the safety consideration of the culvert crossing is based on the theoretical number of crashes, which is, in turn, derived from the relative road width. Further, this appears not to encompass all influencing factors of culvert crossings. While no model can encompass all failure mechanisms, this one seems to neglect important aspects such as scour, sedimentation, corrosion problems, and the physical condition of the culvert.

Summary

The multiple sources examined for this paper all contributed to its development in some unique way. These sources are summarized in the Table 3.

All work on this project to this point has been focused on establishing a background and base level knowledge for the development of a rating system for rural culvert crossing repair and maintenance. The remainder of the document will build on this foundation discussing the methodology, findings, analysis, and conclusion of this project.

Table 3. State of the Practice Review Information Sources

Literature Source	Contribution to Project
FHWA Culvert Inspection Manual	∘ Well-developed program to inspect and monitor culverts greater than 20' in diameter on our nation's highways ∘ Specific maintenance rating scale and thorough inspection of every aspect of culvert failure mechanisms ∘ While analysis is comprehensive, a more efficient system needs to be developed for the vast number of our nation's smaller culverts
Missouri Department of Transportation Culvert Research	∘ Long term material-specific useful life studies ∘ Past results have shown no correlation between pH, abrasion, soil resistivity, chemical properties of runoff, and watershed characteristics and service life ∘ Currently involved in biannual inspection of 230 culverts across Missouri
Montana Department of Transportation Culvert Useful Life Calculator	∘ Useful life calculator factoring in material, soil, and water parameters ∘ Recognizes degradation due to corrosion, but fails to recognize other failures
California Culvert Maintenance-Free Service Life Estimator	∘ Similar to Montana Department of Transportation Useful Life Calculator ∘ Allows compensation for channel flow conditions
FHWA Bridge Management System	∘ A system such as this is a 20 year goal for culvert management ∘ Advanced to point of predicting condition through climate, hydraulic, hydrologic, Geotechnical, and earthquake data
FHWA Pavement Management System	∘ Similar to culvert system in trying to predict condition level without a measurable condition parameter
Micro-Computer Based Culvert Rating System	∘ Only model found to consider multiple failure mechanisms ∘ Cause and effect relationships could use improvement ∘ Only addresses safety and hydraulic capacity, neglects corrosion and other failure mechanisms

CHAPTER 3

METHODOLOGY

This Chapter describes the methodology used for the development of a rural culvert rating system. This project methodology can be divided into three distinct phases; identification of project scope, data acquisition, and data analysis and model formation.

Identification of Project Scope

The early phases of this project were spent in the circular process of determining the project's end goal, testing the feasibility of that goal against available resources, and refining the end goal to match available data and resources. Ideally, the culvert ranking model would output a forecast of useful life or economic reference. A lack of historical data made this type of time-sensitive analysis impossible. Therefore, it was decided to work toward a conditional rating, with a minimal number of inputs. These inputs must be as objective in nature as possible, easy to gather in the field, and accurately describe specific failure criteria.

Data Acquisition

Data acquisition for this project took place in two phases. First, it was necessary to decide what information to collect, then the collection methodology could be developed.

Determination of Culvert Parameters

Before any data could be acquired, the data classification and descriptions of the items to be collected were established. The development of a system such as this is a series of compromises; if every conceivable culvert parameter were used to define culvert condition, the data collection efforts would outweigh the value of results obtained from them. Because the objective of the culvert management system is to set priorities and get a relative ranking of the system's culverts, a more logical approach is to minimize the number of culvert performance or condition parameters collected. This was accomplished by reducing the list to include only the factors that will directly contribute to the most predominant failure mechanisms.

Table 4. Culvert and Site Characteristics included in Data Collection

Culvert and Site Characteristics	
Date of Inspection	Channel Material/Surface Description
Culvert Installation Date	Scour at Outlet
Name of Inspector	Evidence of Major Failure
Cross Dimensional Shape	Evidence of Culvert Settlement
Culvert Material	Degree of corrosion
Interior or Invert Treatment	Coating of Culvert Invert Worn Away
Type of Inlet Structure	Holes in Culvert Invert
System and Route Number	Sedimentation of Cross Section
Reference Point (Mile Post)	Physical Blockage
Height of Culvert	Perched Outlet
Width of Culvert	Joint Separation
Length of Culvert	Damage to Roadway
Cover Height	Erosion or Failure of Side Slope
Culvert Use	Physical Damage to Culvert
Crossing or Stream Name	Evidence of Piping
Detour Length	Presence of Backwater Pool
Average Daily Traffic	

Early in the project it was decided that the primary justifications for including parameters in the model were: the ability of the parameter to summarize a specific culvert condition and the ease of measurement in a field setting. Table 4 summarizes the information that was evaluated for inclusion in the model, data that, if selected, must be collected for any given culvert.

Table 5. Items Excluded From Model Formation

Item	Reason Not Included
Thickness of Pipe	◦ Difficult to measure accurately if culverts have end treatments or other complications ◦ Thickness is typically standardized for specific culvert sizes
Type of Exterior Treatment	◦ Difficult to access after installation, data item should be included in pre-construction documentation
Elevation of Road Bed Over Culvert Outlet Invert	◦ Simplified to cover height, which is closely related to the ease and expense of maintenance
Upstream Geometry (channel width, channel slope, road side slope, ditch back slope)	◦ These items would only be necessary for hydraulic capacity modeling, culvert slope is difficult to measure accurately in the field without surveying equipment
Downstream Geometry (Tailwater depth)	◦ Difficult to access accurately without constant monitoring, only necessary for hydraulic capacity calculations
Vertical and Horizontal Alignment Problems	◦ Purely subjective judgments that would merit repositioning or replacement measures
Potential for Ditch Erosion	◦ Subjective rating related to ditch channel material description
Soil and Effluent pH and Resistivity	◦ Corrosion specific inputs for some models of useful life ◦ Terms would require laboratory analysis of samples or complicated field tests ◦ In order to measure effluent pH and resistivity culvert must be found transmitting water
High Velocity Inlet Flow (as related to fish Passage)	◦ Subjective measure that can be calculated with flow parameters and culvert physical information ◦ Temporary phenomena specific only to fish supporting, permanent or seasonal streams and rivers
Notable change in watershed (above culvert)	◦ Related to overall basin, not one specific culvert crossing ◦ Major changes may trigger other forms of culvert failure, but watershed change is not a failure criteria
Exposure of reinforcing steel (concrete culverts)	◦ Project is designed to handle all culvert materials, and thus material specific analysis must be eliminated
Culvert Soffet Exposed to Road Surface	◦ Due to lack of cover on unpaved roads ◦ Related to road maintenance, not culvert maintenance and performance

Detailed explanations of each parameter, as well as the specific instructions for measurement of each parameter can be found in Appendix A, the Culvert Data Collection Guide. Table 5 shows parameters that were not included in the development data set, with brief descriptions of the reasons for exclusion.

Data Collection

A plan was formulated with the Montana Department of Transportation for a statewide data collection effort by each of the 11 MDT Maintenance Divisions in their respective area. In order for these groups to gather homogeneous data, a thorough Data Collection Guide was compiled (Appendix A). This guide contained specific instructions related to each data input (those in Table 4) as well as to the handling of the data in general. Additionally the Data Collection Guide describes each characteristic explicitly, and briefly relates the theoretical importance of each. The document was introduced by a presentation explaining the scope of the project and distributed to each maintenance division at a semi-annual MDT Maintenance Supervisors meeting. Culverts to be included in the study were selected at random by the respective maintenance personnel. While this did not guarantee an unbiased sample with respect to age, material, and location, it was determined that this minor random bias would not significantly alter the model results. Table 6 summarizes the response rate for each parameter, with comments concerning the reporting of each parameter.

Table 6. Summary of Responses

Parameter Name	Percent Response	Comments
Overall Condition Rating	97%	◦ Subjective overall condition rating ◦ Some inspectors would not give any culvert they inspected a high rating, others seemed to rate them consistently low ◦ Some showed very little variance , even if other parameters seem to very a great deal
Date of Inspection	100%	
Culvert Installation Date	75%	◦ Lack of historical record keeping
Name of Inspector	100%	
Cross Dimensional Shape	99%	◦ Primarily circular culverts inspected
Culvert Material	98%	◦ 61% corrugated metal pipe (CMP) and 37 % reinforced concrete pipe (RCP) reported
Interior or Invert Treatment	98%	◦ Nearly 90% reported no interior treatment
Type of Inlet Structure	98%	◦ Fairly evenly distributed
Road	100%	◦ Designations are according to MDT classification for ease of implementation into future system
Mile Post	99%	◦ Most accurately reported to the nearest tenth of a mile
Average Daily Traffic	97%	◦ Values extracted from MDT geographic information system database
Height of Culvert	100%	◦ Values reported to nearest tenth of a foot.
Width of Culvert	100%	◦ Values reported to nearest tenth of a foot.
Length of Culvert	99%	◦ Values reported to nearest foot, difficult to measure on long culverts.
Cover Height	90%	◦ Estimated value for consideration of repair/replacement plan and cost.
Culvert Use	100%	◦ 70% periodic drainage, 19% stream passage
Crossing or Stream Name	14%	◦ Reported only for named streams and road underpasses.
Detour Length	91%	◦ Set class variables (classes were 0-1.1 miles, 1.1-3.0 miles, 3.1-10 miles, 10.1-50 miles, and over 50.1 miles.)
Channel Material/Surface Description	99%	◦ Many inspectors had difficulty choosing one material description.
Scour at Outlet	98%	◦ Evidence of scour issues in 19% of culverts reported
Evidence of Major Failure	99%	◦ Several major failure mechanisms noted
Evidence of Culvert Settlement	99%	◦ Theoretically difficult to access but evidence reported in 15% of cases
Degree of corrosion	100%	◦ Corrosion issues reported in 18% of cases
Coating of Culvert Invert Worn Away	99%	◦ Only noted in 7.5% of cases
Holes in Culvert Invert	99%	◦ Only reported in 4% of cases
Sedimentation of Cross Section	100%	◦ One of few truly objective parameters, good results
Physical Blockage	100%	◦ One of few truly objective parameters, good results

Table 6. Summary of Responses (continued)

Parameter Name	Percent Response	Comments
Perched Outlet	99%	◦ Reported in 8% of cases.
Joint Separation	98%	◦ Reported in 8% of cases.
Damage to Roadway	99%	◦ Some degree of damage in 7% of cases
Erosion or Failure of Side Slope	100%	◦ Some degree of damage in 11% of cases
Physical Damage to Culvert	99%	◦ Some degree of damage in 16% of cases
Evidence of Piping	99%	◦ Condition noted in only 5% of cases
Presence of Backwater Pool	100%	◦ Pools existent in 14% of cases

Data was returned to the author on the data sheets provided in the Data Collection Guide. All 11 divisions reported data resulting in a sample set of over 460 culverts. The only parameter not gathered in the field by maintenance divisions was the average daily traffic. This was obtained by referencing culvert crossings by system and route number at the appropriate reference point (mile marker) through MDT's GIS database. The information was then input into a spreadsheet for analysis and input into the statistical modeling software, which will be discussed in the next section.

Data Analysis and Model Formation

Much of the early debate in this project concerned the type of statistical model necessary to properly analyze our available data, and return a worthwhile result. One serious obstacle in planning this statistical model was the fact that we had no concrete response variable. Most research endeavors have a measurable resultant value, this project proved more nebulous. No past condition data was available, and due to the time constraints of the project, the model would have to be based on only one round of data acquisition. This ruled out any possibility of returning a time sensitive result, such as useful life. A relative condition rating was the only result possible. The next obstacle

became the type of scale to compare that condition too, with no established ratings criteria and no objective or physical measurement devices. Thus it was decided to rate the culvert conditions in a comparative fashion, a scale that would give the condition relative to others so that maintenance and management decisions could be made. This type of result could be obtained from an ordered probit statistical model.

Ordered Probit Statistical Model

To analyze this situation with a discrete ordered data set an ordered probit statistical model was used. Ordered data must be composed of a countable number of values and these values must describe a range of alternatives. For example, the data could include ordered opinions (i.e. do you agree, are neutral, or agree), categorical frequency data (i.e. never, sometimes, often), or qualitative rankings (i.e. on a scale from 1 to 10). The data can be in either numeric or qualitative form, the qualitative results later being translated into integer values. Application of the standardized or nested multinomial discrete models would not account for the ordinal nature of the discrete data and thus information would be lost. After the data is analyzed, each response has a determinable probability of occurrence.[21] This probability is used to determine what the result will be from subsequent data sets.

Ordered probability models have been used since their development by Zavoina and McElvey in 1975. The technique was initially developed in the field of economics. Ordered probit models define an unobserved variable, y_i^*, such that:

$$y_i^* = \beta X + \varepsilon$$

where,

β is a vector of estimable regression parameters,

X is a vector or measurable characteristics (e.g. condition, quality) that define ranking, and

ε is a random error or disturbance term.

Using this standard equation, various threshold values can be determined to reflect the discrete nature of the data:

$y_i = 0$ if $y_i^* \leq \mu_o$

$y_i = 1$ if $\mu_0 < y_i^* \leq \mu_1$

$y_i = 2$ if $\mu_1 < y_i^* \leq \mu_2$

:

$y_i = j$ if $y_i^* \geq \mu_{j-1}$

where,

y_i is the actual or observed ranking, and

μ is an estimable parameter that defines y (referred to as thresholds).

The μ's are parameters that are estimated jointly with the model coefficients β. The problem then becomes determining the probability of *j* specific ordered responses for each observation *N*. This is accomplished by making an assumption on the distribution of ε. This disturbance term in an ordered probit model is assumed to be have a standard normal distribution with the mean equal to 0 and the variance equal to 1. The ordered selection probabilities are estimated as follows:

$P(y=1) = \Phi(-\beta X)$

$P(y=2) = \Phi(\mu_1 - \beta X) - \Phi(-\beta X)$

$P(y=3) = \Phi(\mu_2 - \beta X) - \Phi(\mu_1 - \beta X)$

:

$P(y=j) = 1 - \Phi(\mu_{j-1} - \beta X)$

where $\Phi(.)$ is the cumulative normal distribution.

In terms of evaluating the effect of individual estimated coefficients in ordered probability models, positive values of β_k imply an that increase in x_κ will increase the probability that the highest ordered discrete category will result and decrease the probability that the lowest ordered discrete category will result.

Further scrutiny needs to be applied to the interpretation of intermediate categories within the ordered probability model. Depending on the location of the thresholds, it is unclear what effect a positive or negative β_k will have on the probabilities of the interior categories.[22]

Software Analysis of Model

Once the model type was established, the data was formatted and input to a DOS based statistical analysis program for calculation. Class variables, including cross-dimensional shape, material, type of inlet structure, use, detour length, and channel surface description were converted into binary variables for each item in the class. For example, cross dimensional shape was divided into corresponding variables categorizing the culvert into circular, rectangular, pipe arch, or arch in shape. Various model trials were analyzed, each with a unique set of parameter combinations, with the resulting

model possessing a sufficiently high rho-squared value, high variable significance and a minimum total number of parameters. Parameters selected had greater than a 95% level of significance, corresponding to a t-statistic of greater than 1.96.

The software was easy to use, but had limitations. First, any row of data (data in all categories for one culvert) that was missing any one of the parameters included in the model calculation, was subsequently removed from the data set prior to the analysis. For example, if the individual gathering data failed to enter a value for degree of scour at the outlet, with this parameter included in that trial of the model, all data points related to that culvert were not considered. Second, the inclusion of a complete set of class variables (i.e. all culvert shapes) would result in a singularity in Hessian error. Therefore it was impossible to analyze the effect of all variables in one class during one model trial, various combinations had to be run and the comparison done of the group of data.

Inclusion of Weighting Parameters

While the average daily traffic (ADT) traversing a culvert crossing and the detour length around the culvert crossing do not directly influence culvert condition, they are important factors in deciding the relative importance of maintenance or replacement should the culvert fail. In order to include these two parameters it was necessary to adjust the results of the statistical model to reflect this importance.

This was done by calculating a rating term which would adjust the overall ranking 25 percent positively or negatively, the importance of attention increasing for roadways with large volumes of traffic and long detour lengths, and decreasing for low volume roadways and short detour lengths. The class variables are shown in Table 7.

Table 7. Class Variable Definition of ADT and Detour Length Variables

ADT Class Variable		Detour Length Class Variable	
Class Variable Value	**ADT Range (vehicles per day)**	**Class Variable Value**	**Detour Length Range**
1	0 to 500	1	0 to 1.0 miles
2	501 to 2000	2	1.1 to 3.0 miles
3	2001 to 5000	3	3.1 to 10.0 miles
4	5001 to 10,000	4	10.1 to 50.0 miles
5	Over 10,000	5	Over 50 miles

The values for ADT were separated into classes, similar to those the detour length was classified into during data acquisition. This resulted in the two variables being in relatively equal scales for the adjustment factor calculation. Various linear and power relationships were calculated, with the goal of a weighting factor with an average equal to 1 and a 25 percent spread on either side. The resultant weighting factor formula was found to be:

$$W=((\text{ADT class variable} + \text{Detour length class variable})/R)^S$$

where,

W is the weighting factor to be divided into the overall condition rating,

ADT class variable corresponds to the ADT of the road in Table 7,

detour length class variable corresponds to the detour length of the road in Table 7,

R is the term which centers the average about a specific term and,

S is the value which will vary the range of the overall weighting factor.

In order to find a function that met the aforementioned criteria, various power functions were analyzed. Equal weight was placed on each factor and the sum of the two class variables was then divided by a value R, to center the term on the value of 1. Next, in order to adjust the spread of the weighting parameter, into the proposed plus or minus

25 percent, the previous value was raised to a value S. When this weighting parameter was analyzed over the sample data, values of R = 4.9 and S = 1/3 were found to be appropriate.

The values of R and S can be varied according to the data set, and the emphasis wished to be placed on weighting according to ADT and detour length.

CHAPTER 4

FINDINGS

This Chapter summarizes the findings of the statistical model. For ease of examination, data items found to statistically reinforce the model (included in final model) and those found to not benefit the final model (excluded from final model) will be presented in tabular format. By convention, with the condition rating being 1 as worst condition and 5 as best condition, and the input variables all being related to degradation of the system, variables should show a negative correlation to the condition. Thus variables exhibiting a positive or near zero correlation were considered insignificant, with reinforcement by the t-statistics output by the statistical program.

Results from Ordered Probit Model

Table 8. Results from Ordered Probit Model

Condition Rating	**Threshold Values**	**Ordered Selection Probabilities**	**Observed Condition Ratings**	**Predicted Values from Initial Data Set**
1	$Z \leq 0$	0.3%	1.9%	1.9%
2	$0 < Z \leq 1.16$	1.1%	5.3%	2.5%
3	$1.16 < Z \leq 2.26$	10.8%	13.0%	8.3%
4	$2.26 < Z \leq 3.98$	58.6%	42.0%	44.4%
5	$Z > 3.98$	29.5%	38.0%	42.9%

The final model resulted with a 57.2 percent rho-squared value, which is a relationship of the initial and final log likelihood values relating the fit of the model to the

sample set data. A rho-squared value of 100 percent would imply a perfect fit. Nine parameters were found to be statistically significant. Overall it matched 61.7% of conditions correctly with those rated in the field. Table 8 summarizes the model results including threshold values and ordered selection probabilities.

Parameters Statistically Eliminated from Model

The summary of Table 10 reinforces statistical elimination from the model. It is important to note, however, that exclusion from the statistical model in most cases does not merit exclusion from a culvert inventory database, as the vital parameters in a inventory database are typically different from those used in modeling. Also, small sample size may not have captured all critical parameters.

Parameters Contributing to Model Results

The parameters summarized in Table 9 were found to significantly contribute to the model. They were chosen according to their level of influence in each model, as well as their logical correlation trends.

The results showed that the four most significant parameters are sedimentation of the cross section, physical blockage, age, and scour at outlet. All but age are parameters that are easily noticeable from outside the culvert barrel, and age is a purely objective parameter that is related to various forms of degradation. Parallel with the initial goals of this project, these parameters represent a minimal amount of data items that will need to be collected for a conditions rating. Some parameters that either had historically or academically been established as important in culvert failure were not found to be of

statistical importance in this analysis (Table 9). While ordered probit models assume complete independence between input variables, some variables selected could be proven to have some interaction. For example, physical damage to the culvert may influence the degree of sedimentation. These interactions are infrequent and are assumed to be statistically insignificant in this model.

Table 9. Culvert Parameters Statistically Eliminated from Model

Parameter	Reasons Reinforcing Elimination
Cross Dimensional Shape	∘ Culvert performance issues are directly tied into culvert shape ∘ Independent of culvert condition
Culvert Material	∘ Correlation of any one material to condition would be to specify one material as having a better condition than the others.
Interior or Invert Treatment	∘ Amount of responses corresponding other than the "No Treatment" responses were statistically too few to be considered significant
Type of Inlet Structure	∘ Found not to contribute to the accuracy of the model. ∘ Future models should include more types of inlet structures.
Height, Width, and Length of Culvert	∘ Physical dimensions do not influence condition ∘ Factor in the cost and ease of maintenance and replacement.
Cover Height	∘ Important factor in the cost analysis of culvert repair/replacement ∘ No direct relation to culvert condition
Culvert Use	∘ Functional classification does not influence condition
Channel/Surface Description	∘ Initially selected a because of its relationship sedimentation, scour, and other failure mechanisms ∘ Secondary relationship found to have no correlation to condition.
Evidence of Major Settlement	∘ Difficult to access in the field ∘ Found to be independent of condition.
Holes in Culvert Invert	∘ Found to not influence condition ∘ Result may be skewed due to less than 5% of the culverts were reported to have holes
Perched Outlet	∘ Nearly 10% of culverts inspected were found to have perched outlets ∘ Found statistically not to contribute to condition. ∘ Further studies recommended on culverts in permanent or semi-permanent streams in relation to fish passage
Damage to Roadway	∘ Secondary indicator found not to contribute to the condition ∘ Does not specifically imply any one failure mechanism, but an easy to observe indicator of several possible degradations
Erosion or Failure of Side Slope	∘ May exhibit improper design, construction, or material issues ∘ Found to not contribute to condition
Evidence of Piping	∘ Found in very few cases, possibly due to recent mitigation efforts
Presence of Backwater Pool	∘ This was the only factor with a positive (albeit small) correlation to condition ∘ No logical reason for a better condition rating due to a backwater pool exists.

Table 10. Parameters Included in Final Model

Parameter	Range of Response	Coefficient	T statistic	Explanation
Age of Culvert	1 to 69 years	-0.0149	3.7905	∘ Material deterioration over time leads to decrease in condition ∘ Third leading parameter for predicting culvert condition
Scour at Outlet	0, 1, or 2	-0.513	3.7010	∘ Scour is an easily noticeable due to its location outside the culvert barrel ∘ Fourth most influential parameter predicting culvert condition.
Evidence of Major Failure	0 or 1	-0.897	2.9413	∘ Encompasses overtopping failure, buoyancy, structural collapse, and others. ∘ Impractical to separate parameters as only reported in about 6% of the cases.
Degree of Corrosion	0, 1, or 2	-0.481	2.8532	∘ Initially flagged as leading cause of culvert failure in Montana, model backs up statement. ∘ Irreversible damage can only be mitigated by lining or replacement of culvert.
Invert of Culvert Invert Worn Away	0, 1, or 2	-0.490	1.8633	∘ Direct relation to abrasive power of stream.
Sedimentation of Cross Section	0 to 100%	-0.0207	4.9606	∘ Exerted greatest influence of all parameters in determination of culvert condition ∘ Dependent on maintenance activities to clean out, but can be traced to design deficiencies that could have prevented.
Physical Blockage	0 to 100%	-0.0155	4.2495	∘ Second only to Sedimentation in influence of model result ∘ Restricts hydraulic capacity, and thus could be a factor in overtopping, etc. ∘ Most physical blockage is impossible to prevent, but its effects can be limited with timely maintenance.
Joint Separation	0 or 1	-0.472	1.9686	∘ Difficult to access, but irreversible damage that can lead to costly road damage.
Physical Damage	0, 1, or 2	-0.406	2.4459	∘ One of only human caused parameters, damage can encourage sedimentation and physical blockage while limiting hydraulic capacity.
Average Daily Traffic (ADT)	1 to 5	(included after statistical model)		∘ Not a measure of condition, but of importance in the determination of prioritization of multiple culverts. ∘ Combined into a weighting factor with detour length.
Detour Length	1 to 5	(included after statistical model)		∘ If culverts fail, the stream/ditch/canal they convey will block traffic and alternate routes will become necessary. ∘ Combined into a weighting factor with detour length.

Examples of Model Mathematics

In order to demonstrate the mathematics of the model, this section will analyze the condition of two culverts from the initial data set. While ordered probit models are similar to linear regression models, the difference lies in the second-stage probability estimation (i.e., the predicted dependent variable being placed into the original ordered dependent variable range, 1-5). Please note that this example is not a validation of the model, as the culverts used were included in the sample set used to develop the initial model.

Table 11. Summary of Parameters, Ranges, Field, and Model Data

	Column A	Column B	Column C	Column D	Column E	Column F
	Parameters	Data Range	Culvert A		Culvert B	
			Field Data	Model Data	Field Data	Model Data
Ordered Probit Model	Overall Condition Rating	1 to 5	5	5	2	2
	Model Intercept	1	Intercept Value (βo)	1	Intercept Value (βo)	1
	Culvert Age	Integers greater than 0, in years	2000-1988	12	2000-1955	45
	Scour at Outlet	0, 1, or 2	0	0	0	0
	Evidence of Major Failure	0 or 1	0	0	1	1
	Degree of corrosion	0, 1, or 2	0	0	1	1
	Coating of Culvert Invert Worn Away	0, 1, or 2	0	0	1	1
	Sedimentation of Cross Section	0 to 100%	2%	2	25%	25
	Physical Blockage	1 to 100%	0	0	20%	20
	Joint Separation	0 or 1	0	0	0	0
	Physical Damage to Culvert	0, 1, or 2	0	0	1	1
Weighting Parameter	Detour Length	5 Classes given in Table 7	10.1 to 50.0 miles	4	0 to 1.0 miles	1
	Average Daily Traffic	Sample data range 10 to 16970 vehicles	1500	2	690	2

Table 11 outlines the parameters used in the model along with the range of data that could be included for each in columns A and B. The model intercept is not a measured parameter, but is the intercept term of the regression model. The remaining terms are parameters that proved significant in the model. The parameters excluded from the model (summarized in Table 9), are excluded. Column's C and E contain data from the sample set. The translation of these field gathered values into values that can be used by the model are found in column's D and F. The top portion refers to parameters involved in the ordered probit model, while the bottom two rows deal specifically with the weighting parameter.

Table 12. Estimated Coefficients and Model Results

Column G	**Column H**	**Column I**	**Column J**
Parameter	**Coefficients**	**Model Results**	
		Culvert A	**Culvert B**
Overall Condition Rating		4.428	0.873
Model Intercept	4.65	4.65	4.65
Culvert Age	-0.015	-0.18	-0.67
Scour at Outlet	-0.51	0.00	0.00
Evidence of Major Failure	-0.90	0.00	-0.90
Degree of corrosion	-0.48	0.00	-0.48
Coating of Culvert Invert Worn Away	-0.49	0.00	-0.49
Sedimentation of Cross Section	-0.021	-0.04	-0.52
Physical Blockage	-0.016	0.00	-0.31
Joint Separation	-0.47	0.00	0.00
Physical Damage to Culvert	-0.41	0.00	-0.41
Detour Length	R= 4.9 S=1/3	Weighting Parameter A= 1.0627	Weighting Parameter B = 0.8434
Average Daily Traffic			

In order to calculate the weighting parameter it was necessary to break the results from the parameters "Detour Length" and "Average Daily Traffic" into class variables. These class variable were described in Table 7. A summary of the derivation of the weighting parameter function can be found in Chapter 3.

Analysis by the ordered probit model resulted in estimated coefficients (β_n, Column H of Table 12) to be applied to each data point, as well as estimated threshold values (μ_i, Table 13) in order to classify the model results into condition rankings. Model results (Columns I and J of Table 12) are the result of the summation of the model data term (Columns D and F of Table 11) multiplied by their respective coefficient (Column H of Table 12) consistent with the form:

$$y_i^* = \beta X.$$

Table 13. Model Thresholds

Model Threshold Values	
Condition Rating	**Threshold Values** (of the form $\mu_i < Y_i^* \leq \mu_{i+1}$)
1	$Y_i^* \leq 0$
2	$0 < Y_i^* \leq 1.16$
3	$1.16 < Y_i^* \leq 2.26$
4	$2.26 < Y_i^* \leq 3.98$
5	$Y_i^* > 3.98$

This value of Y_i^* was fit between two threshold values that would define the condition of the culvert (Table 13). Ordered selection probabilities were computed with a standard normal distribution and were reported in Table 8.

Table 14. Calculation of Condition Rating and Adjusted Condition Rating

Final Rating	Culvert A	Culvert B
Condition from Model	5	2
Weighting Parameter	1.0627	0.8434
Adj. Condition Rating	4.71	2.37

Application of the weighting parameters (as calculated in Table 12) resulted in the final model condition ratings to be divided by their respective weighting parameter, and resulting in an adjusted condition rating. This final step is shown in Table 14. Thus, the interpretation of the example results is that culvert A is in relatively good shape, while culvert B is a higher candidate for repair or maintenance.

Model Shortcomings

Analysis of the model has revealed several shortcomings. First the model was forced to use a subjective dependent variable. With no set parameter able to quantify culvert condition, the 1-5 condition rating was used. Secondly, some predictor parameters are semi-subjective. The initial goal was to use only purely objective parameters, but some failure mechanisms could not be represented by measurable characteristics. This subjectivity can be reduced through uniform education of all inspectors, establishing a baseline for their interpretation of damage. Lastly, the model considers the contribution of individual failure characteristics in combination. When only a single failure characteristic exists, albeit controlling or catastrophic, the model returns a relatively high culvert ranking. For example, a culvert with 100% sedimentation of the cross section and no other deficiencies would return a Y_i^* value of 2.55 which would fit into the threshold

values of a condition rating of 4. This clearly is not representative of the importance of maintenance for this culvert.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The final product of this research is only a small contribution to the potential breadth of this subject. Knowledge of the culvert parameters found to significantly influence culvert condition also provides insight to the predominant failure mechanisms of the culverts sampled. But due to the inherent subjective nature of this system, the ratings are also influenced by the individual inspector's perception of which failure mechanisms are the most important. Accurate monitoring of the actual culvert replacements and maintenance over time and the causes of this attention will provide a better baseline for the specific characteristics to closely monitor. After this data has accumulated for a significant period of time, specific failures will be apparent, and parameters to measure the degree of these failures can be established. This would be a more deterministic approach, as compared to the probabilistic approach this project was forced to take, and would more than likely result in a better overall model.

Research into this topic should continue to evaluate the interaction between condition ratings and service life of culverts. This can only be accomplished through additional rounds of data collection, to determine the time dependence on the various forms of deterioration. The cause and effect relationship of time dependence is appropriate for some instances, for example corrosion, but quite often catastrophic culvert failures are event driven, such as when a 100 year storm occurs. While these events are summarized

by their probabilities over lengths of time, they are caused by the event itself, and not the time that separated it from the previous one.

As demonstrated by the overwhelming amount of inquiries during this project's development, culvert management is a very important topic to those who manage our nation's transportation infrastructure. The development process of this project has attempted to stay general enough for its application into a wide variety of transportation organizations.

When the Federal Highway Administration began to develop pavement and bridge management systems over 30 years ago, they looked at the complex task of decoding the interactions between their structures, the traffic that used them, and the surrounding environment as daunting. But in those 30 years they have developed systems that accurately predict and analyze useful life and condition results. The same can be done with culverts. Hopefully using the knowledge and experience gained from these and other systems, the development of an accurate culvert management system does not take as long.

Recommendations for Continued Research

Recommendations for continued research into this topic include:

- Examination into similar parameters in a similar sized, if not larger sample set over a determinant time interval, in order to establish some sort of time dependence on condition.

- Investigation into other types of dependence, beyond time, that may include spatial, environmental or event driven relationships.
- Application of this project's findings to other geographical regions in order to determine the range of its applicability.

Due to the complex hydraulic nature, as well as the interaction with the natural environment, there may never be a 100 percent accurate model for the determination of culvert condition or service life. As found by the Missouri Department of Transportation, no system for the accurate determination of serviced life has been developed. But continuing research into this matter will eventually develop a system that will assist personnel in the maintenance, planning, and finance divisions to see a more accurate picture of culvert condition, and enable them to do their respective jobs more precisely and efficiently.

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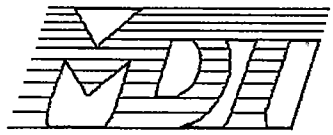
APPENDICES

APPENDIX A

CULVERT DATA COLLECTION GUIDE







Culvert Data Collection Guide

INTRODUCTION

A joint effort between the Montana Department of Transportation (MDT) and the Western Transportation Institute (WTI) at Montana State University (MSU) is underway to develop a formalized rating system that proactively addresses the repair and maintenance needs of culverts. In developing such a rating system, the first step is to record both an overall culvert condition rating and various culvert and site specific characteristics (i.e., shape, size, sedimentation, etc.) for a small sample of culverts throughout the state. This data will be used to determine the specific culvert and site characteristics that lead to a decline in culvert condition. Once these initial relationships are established, an overall condition rating can be predicted for any culvert in the state using only its respective culvert and site characteristics. This overall condition rating will ultimately be used to prioritize culvert repair and maintenance activities.

BACKGROUND

Culverts are an important supplement to the visible network of roads and structures that convey vehicles providing effective and inexpensive passage over small streams and rivers. As such, culverts are widely used by state, county, local, park, and forest service agencies. The Montana Department of Transportation (MDT) alone utilizes over 30,000 culverts as part of the state roadway system. Similar to bridges, culverts should be inspected periodically to assess the need for maintenance, repair or replacement. Should culverts go unchecked and be allowed to fail and result in road closure, mobility for travelers is compromised, particularly in rural or remote areas where alternate routes are often unavailable. Further, maintenance costs are predictably higher for failed culvert

repair as compared to routine or preventative culvert maintenance. Cost savings can be significant; MDT estimates spending $500,000 per year on culvert-related maintenance.

Water flow through culverts is typically divided into two classes: inlet controlled and outlet controlled. Figures 1 and 2, on the following page, provide general culvert cross sections and respective terminology used throughout this guide. **Inlet control** conditions result when the culvert barrel permits more flow than the inlet allows. **Outlet control** conditions result when conditions downstream of the culvert control flow rates or the culvert barrel controls the flow limit. Hence, the inlet and outlet condition are critical in determining its capacity.

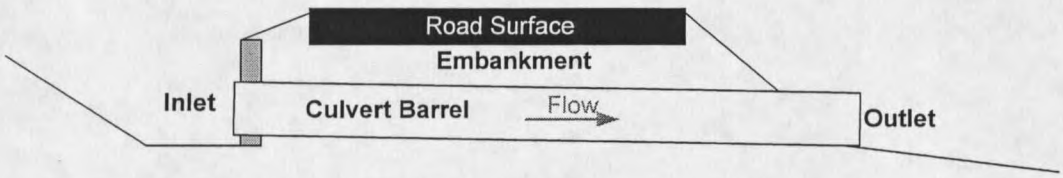


Figure 1.

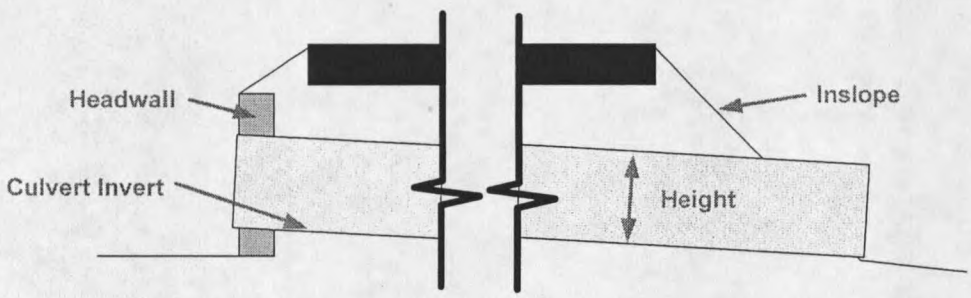


Figure 2.

DATA COLLECTION PROCEDURES

STEP 1. Designate a team of individuals to participate.

Only a two-person team should be responsible for the collection of all data from each division. If possible they should be experienced in culvert maintenance and repair. This will limit potential subjectivity and variability in the data collected.

STEP 2. Select a sample of no less than 40 culverts to inspect.

Each division is asked to collect data for no less than 40 culverts. All culverts must be MDT-owned and maintained. Do not include private culverts. Though not truly randomly sampled, please select a good mix of culvert size, shape, and material for inspection. However, do not include culverts constructed of masonry, wood or stone and do not include culverts in excess of 20 feet in diameter.

STEP 3. Read the information contained in this Guide fully.

It is essential to read this guide carefully prior to starting your data collection efforts. Because several different individuals from around the state will be collecting information to be entered in a common database, its important that you all use the same terminology and follow the same procedures for collecting and recording data. Should you have any questions regarding terminology, procedures or other concerns after reviewing this guide, please feel free to call or email Mr. Dan Baker, Graduate Research Assistant, at (406) 994-7378 or email at dan_b@coe.montana.edu.

STEP 4. Per culvert, record an overall condition rating of 1 through 5.

Overall condition ratings are defined as follows:

CONDITION INDEX	GENERAL DESCRIPTION	DESCRIPTION
1	Poor	Culvert is in dire need of prompt repair or full replacement. Its deficiencies threaten to disrupt or are hindering traffic flow. Damage needs to be repaired as soon as possible.
2	Below Average	Culvert condition indicates need for repair. While it is still in operating condition, its condition shows potential for additional deterioration.
3	Fair	Culvert is still operating, but could use some maintenance to restore it to full potential. Adverse conditions could cause major problems.
4	Good	Culvert shows minor deficiencies, with continued periodic maintenance culvert should be trouble free.
5	Excellent	Culvert shows no signs of problems. Water is flowing, or could flow at full capacity with no chance of interrupting traffic flow.

Once initial relationships are developed between the overall condition rating and various culvert and site characteristics for this sample of culverts, an overall condition rating can be predicted for any culvert statewide using only its culvert and site characteristics.

STEP 5. Record the various culvert and site characteristics for each culvert.

A predefined list of culvert and site characteristics is solicited on the data collection forms contained within this guide. Data is entered either as short answers, YES or NO, or qualitative ratings that are described in the pages to follow. Note the completed example data collection form on the next page. By general estimate it should take no more than 30 minutes per culvert to collect all data. As described previously you are asked to provide an overall condition rating for each of the 40 culverts in your division. The only materials required for data collection will be this manual, the attached forms, and a tape measure.

In these measurements, we are looking at the worst case scenario. For example if the data input requires rating of the degree of siltation, and the upstream end is completely covered, but the downstream end is open, we will rate the upstream end.

STEP 6. Return completed data forms.

When completed with the data collection, please return all forms to:

Dan Baker
c/o Western Transportation Institute
MSU Bozeman
PO Box 173910
Bozeman, MT 59717-3910

Office Phone: (406) 994-7378
Email: dan_b@coe.montana.edu

Please return the completed data collection forms no later than October 30, 2000. Thank you very much for your assistance.

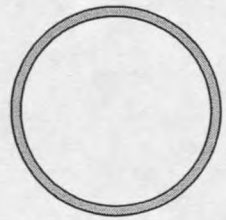
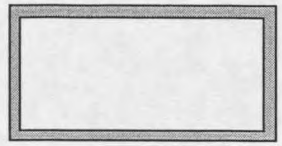
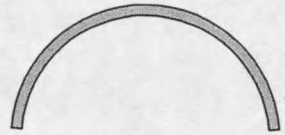
Culvert and Site Characteristics

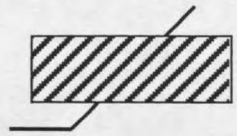
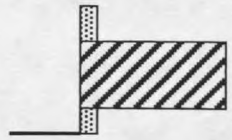
Overall Condition Rating		Poor 1 2 3 (4) Excellent 5	
1	Date of Inspection	09 18 2000	
2	Culvert Installation Date	10 1975	
3	Name of Inspector	Baker, D	
4	Cross Dimensional Shape	(Circular)	Pipe Arch
		Rectangular	Arch (Open Bottom)
5	Culvert Material	(Galvanized Corrugated Steel Pipe)	Ribbed High Density Polyethylene (HDPE)
		Reinforced Concrete Pipe (RCP)	Other:
		Corregated Aluminum Pipe (CAP)	
6	Interior or Invert Treatment	(No Invert Treatment)	Concrete Lined
		Spray on Bituminous Asphalt	Natural Bed Material
		Asphalt Cement Pavement	Other:
7	Type of Inlet Structure	Projecting	Mitered
		(Flush)	
8	System & Route	P-50	
9	Reference Point	115.3	
10	Height of Culvert	3.5	feet
11	Width of Culvert	3.5	feet
12	Length of Culvert	59	feet
13	Cover Height	7	feet
14	Culvert Use	(Stream Passage)	Stock Passage
		Periodic Drainage	Road Underpass

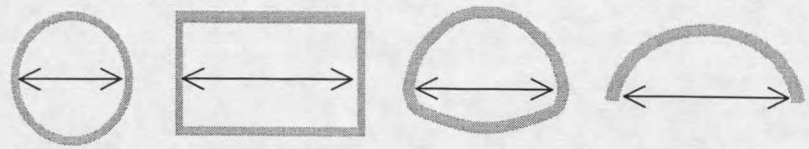
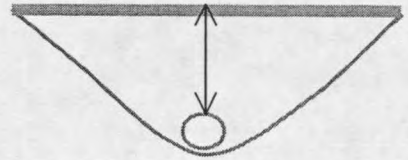
Notes:

Culvert and Site Characteristics

15	Crossing or Stream Name	Big Creek		
16	Detour Length	0 to 1.0 miles		10.1 to 50.0 miles
		1.1 to 3.0 miles		over 50.1 miles
		(3.1 to 10.0 miles)		
17	Channel Material/Surface Description	(Grass)		Gravel
		Brush and/or Trees		Dirt
		Cobbles		Lined (Concrete or AC)
18	Scour at Outlet	(No Damage 0)	1	Serious 2
19	Evidence of Major Failure	YES		(NO)
20	Evidence of Culvert Settlement	(0)	1	2
21	Degree of corrosion	0	(1)	2
22	Coating of Culvert Invert Worn Away	0	(1)	2
23	Holes in Culvert Invert	YES		(NO)
24	Sedimentation of Cross Section	10 %		
25	Physical Blockage	0 %		
26	Perched Outlet	YES		(NO)
27	Joint Separation	YES		(NO)
28	Damage to Roadway	(0)	1	2
29	Erosion or Failure of Side Slope	(0)	1	2
30	Physical Damage to Culvert	0	(1)	2
31	Evidence of Piping	(0)	1	2
32	Presence of Backwater Pool	YES		(NO)

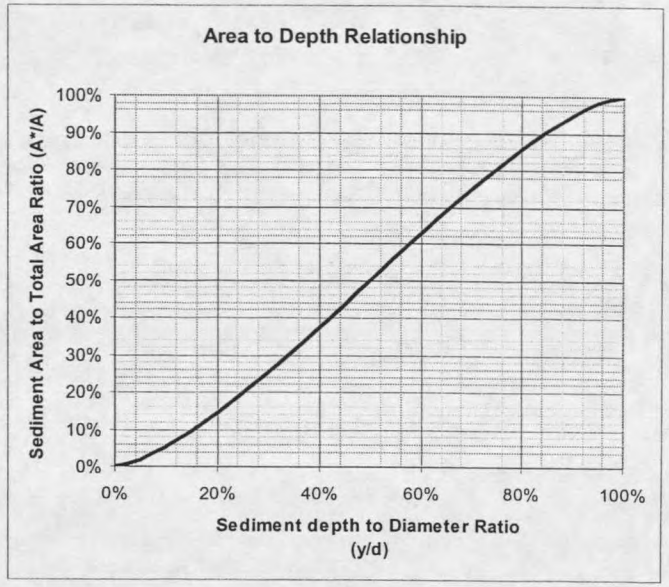
Culvert and Site Characteristics				
	Input Name	**Description**	**Notes:**	
1	**Date of Inspection**	Date in form: MM-DD-YYYY		
2	**Culvert Installation Date**	Date in form: MM-YYYY	This data may be impossible to gather in the field. Culverts are typically evaluated for repair or replacement every time a road is resurfaced or reconstructed. Most culverts along the same route should have approximately the same installation date. *Approximations only allowed when impossible to determine installation date.*	
3	**Name of Inspector**	Last Name, First Initial	This information allows others to review who made the measurements.	
4	**Cross Dimensional Shape**	<u>Select one of following:</u> • Circular • Rectangular • Pipe Arch • Arch (Open Bottom)	Circular 	Pipe Arch 
			Rectangular 	Arch (open bottom) 

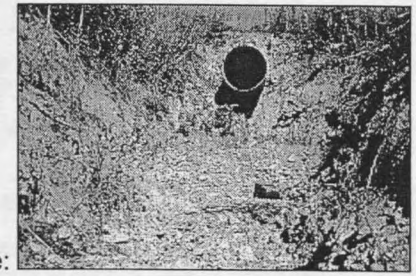
5	**Culvert Material**	Select one of following: • Galvanized Corrugated Steel Pipe • Reinforced Concrete Pipe (RCP) • Corregated Aluminum Pipe (CAP) • Ribbed High Density Polyethylene (HDPE) • Other (Please List)	Culvert materials listed are typical of those used by MDT. Please list if other material was used.
6	**Interior or Invert Treatment**	Select one of following: • No Invert treatment • Spray on Bituminous Asphalt • Asphalt Cement Pavement • Concrete Lined • Natural Bed Material • Other (Please Describe)	In order to increase abrasion and corrosion resistance in some culverts they receive interior treatments, mainly concentrated on the invert. Indicate which treatment the culvert is supposed to have. *Only select "Natural Bed Material" if culvert is designed to contain natural material.*
7	**Type of Inlet Structure**	Select one of following: • Projecting (Culvert Inlet Projects Into Channel • Flush (Culvert Inlet Is Flush With Vertical Headwall) • Mitered (Culvert Is Mitered Flush With Embankment)	If inlet is different from those listed, select most similar type. Projecting  Flush  Mitered 

8	**System and Route Number**	MDT System Route #	Do NOT use common designation (ex. Do not use US 191, but P-50 instead)
9	**Reference Point**	Number in miles. *Accuracy to 0.1 mile or greater if possible.*	This is the primary means of identifying each culvert. The distance between reference points (commonly known as mile markers) may be measured by automobile.
10	**Height of Culvert**	Maximum inside height of culvert barrel. *Accuracy to 0.1 feet.*	
11	**Width of Culvert**	Maximum inside width of culvert barrel. *Accuracy to 0.1 feet.*	
12	**Length of Culvert**	Culvert length from inlet to outlet invert. *Accuracy to 0.1 feet.*	Measure as accurately as possible. Some situations and placements may require approximate methods.
13	**Cover Height**	Average Height from top of culvert to road surface. *Accuracy to 0.1 feet.*	
14	**Primary Culvert Use**	<u>Select from the following:</u> • Stream or other waterway passage • Periodic Drainage • Stock Passage	Culverts are installed for a wide variety of reasons. Please indicate the primary use only.

		◦ Road Underpass	
15	**Crossing or Stream Name**	Simple name of crossing (cross road or waterway).	Name location (if any) of crossing. If crossing name unknown leave blank.
16	**Detour Length**	<u>Select from range below:</u> ◦ 0 to 1.0 miles ◦ 1.1 to 3.0 miles ◦ 3.1 to 10.0 miles ◦ 10.1 to 50.0 miles ◦ over 50.1 miles	This is the distance in miles a vehicle would be required to travel to reach the other side of the crossing, if the culvert crossing were closed or had failed. Use area maps to accurately estimate the distance.
17	**Channel Material/Surface Description**	<u>Select one of following:</u> ◦ Grass ◦ Brush and/or Trees ◦ Cobbles ◦ Gravel ◦ Dirt ◦ Lined (Concrete or AC)	Select predominant channel description of upstream and downstream channels.
18	**Scour at Outlet**	Qualitative rating of degree of scour of channel material at <u>outlet.</u> *(0, 1, or 2)*	High velocity water exiting a culvert may erode non-protected channel material. <u>Rate as follows:</u> **0.** No indication of scouring at outlet. **1.** Moderate scour. Limited amount has occurred but does not appear to continue. **2.** Major scour concerns, problem continues to wash away bed material.

19	**Evidence of Major Failure**	Indicate evidence of former major hydraulic failure. *(Yes or No)*	Failures may include: • **Overtopping**: Backwater of culvert increases beyond height of roadbed. Water flows over road and may result in erosion of the road surface or shoulders. • **Buoyancy Failure**: Uplift forces in culvert due to trapped air either bend ends of culvert up, or displace entire culvert. • **Structural Collapse of Barrel**: Culvert barrels must support the weight of the above roadway. And major deformation can be considered collapse as the culvert's strength is primarily attributed to its shape. During major flow events drainage may overwhelm the capacity of the culvert and a hydraulic failure results. Typically one failure can lead to another.
20	**Evidence of Culvert Settlement**	Indicate qualitative level of settlement problems. *(0, 1, or 2)*	Settlement can be localized (just the culvert itself settling), or the culvert may settle as the entire roadbed subsides. Settlement typically is caused by the consolidation of unfit building materials over time. Rate settlement as follows: **0.** No apparent settlement. **1.** Minor localized settlement of culvert, culvert still functional. **2.** Settlement of roadbed or major settlement of culvert, resulting in reduced hydraulic capacity of culvert.
21	**Degree of Corrosion**	Indicate degree of soil side or water side corrosion. *(0, 1, or 2)*	Rate degree of corrosion: **0.** No corrosion visible. **1.** Minor corrosion problems. **2.** Major corrosion damage.

22	**Coating of Culvert Invert Worn Away**	Indicate degree of culvert lining material being washed or worn away. *(0, 1, or 2)*	Culverts may be lined as described in item #7. These linings are subject to wear and tear, mainly on the invert of the culvert. Include in this rating the galvanized coating on typical CSP. <u>Rate the condition of the lining as follows:</u> **0.** No damage to culvert lining. **1.** Minor damage to invert material. **2.** Majority of coating worn away.
23	**Holes in Culvert Invert**	Observe presence of holes through the culvert barrel. *(YES or NO)*	Holes are typically caused by abrasion and/or corrosion in the invert of the culvert.
24	**Sedimentation or sod blockage as percentage of cross section**	Estimate maximum cross sectional blocked by sediment or sod as a percentage of flow area. *(0% to 100%)*	As height of blockage to area of blockage is not a linear relationship, refer to graph below. 

25	**Physical Blockage**	Estimate Maximum cross sectional blocked by large debris as a percentage of flow area. *(0% to 100%)*	When possible remove obstructions during inspection. Only include physical blockage that is impossible to remove during inspection.
26	**Perched Outlet**	Determine if invert of outlet lies notably above downstream channel *(YES or NO)*	Perched outlets inhibit fish passage and also contribute to scour effects. Example photo of extreme case: 
27	**Joint Separation**	Indicate presence of joint separation *(YES or NO)*	Joint separation is the physical separation of different sections of culvert along the barrel. It typically is cause by differential settlement or improper construction. This separation can lead to a variety of problems such as infiltration.
28	**Damage to Roadway Immediately Above Culvert**	Degree of damage to roadway due to culvert. *(0, 1, or 2)*	Damage to the roadway above the culvert is of major concern to the safety of road users. It also is a primary indicator of several failure mechanisms that would otherwise go unnoticed. Damage can include sagging of the guardrail and pavement, and transverse or alligator cracking of the pavement. Worst cases could include potholes in the pavement. <u>Rate the degree of damage as follows:</u> **0.** No evidence of damage caused by culvert failure. **1.** Minor or possible damage caused by culvert. **2.** Major roadway damage caused by culvert.

29	**Erosion or failure of Side Slope**	Degree of damage to road inslopes adjacent to culvert location. *(0, 1, or 2)*	Side slopes that are improperly protected are easily eroded by backwater pools at the upstream end of culverts or by scour effects or backwater at the downstream end. This erosion may propagate into sloughing of the road cut or fill slopes. Rate degree of damage as follows: **0.** No damage to slopes adjacent to or above culvert. **1.** Minor damage to slopes adjacent or above culvert. **2.** Major damage to side slopes adjacent or above culvert.
30	**Physical damage to culvert**	Degree of physical damage to end treatments or culvert barrel *(0, 1, or 2)*	Physical damage is typically caused by large debris attempting to flow through the culvert, by cars leaving the roadway, or improper road and ditch maintenance activities. Severity of the damage can be limited to simple bent or broken outlet or inlet, or as major as complete collapse of the damaged sections. If the disrepair may be corrected on site no major repair will be merited. Rate physical damage as follows: **0.** No physical damage to culvert. **1.** Minor physical damage to culvert, unlikely to inhibit flow. **2.** Major physical damage to culvert, requires repair or replacement.

31	**Evidence of Piping**	Degree of piping in culvert. *(0, 1, or 2)*	Piping is the flow of water around (instead of through) the culvert barrel. The two primary reasons for piping are deficient end treatments or poorly compacted fill immediately around the culvert. As water is piped around the culvert, it begins to carry away the fine fill around the culvert barrel. This creates instability and structural problems around the culvert, and for the road surface. Piping can be diagnosed at the ends of the culvert by the undermining of the culvert invert, or material loss around the culvert barrel. The easiest indicator would be notable water flowing around the culvert barrel. <u>Rate piping as follows:</u> **0.** No evidence of piping **1.** Minor or possible evidence of piping. **2.** Major piping problems.
32	**Presence of Backwater Pool During Normal Flows**	Presence of backwater pool at outlet end of culvert. *(YES or NO)*	Backwater pools create problems with sedimentation, corrosion and piping. Indicate if backwater pool is present, or is usually (>75% of the time) at this location. Example of backwater pool: 

APPENDIX B

AN EXCEL TEMPLATE FOR GENERATING RATING CURVES FOR CORRUGATED-METAL-PIPE CULVERTS

An Excel Template for Generating Rating Curves for Corrugated-Metal-Pipe Culverts

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As a convenient and inexpensive method of intersecting roads and waterways, culverts occur in many shapes and sizes. Culverts range from arch-shaped concrete structures big enough to drive a truck through to circular pipes as small as six inches in diameter. Because of low cost, high endurance to the elements, and installation ease, circular-shaped corrugated-metal-pipe culverts are commonly used in Montana. The Excel template described herein will provide designers with a simple tool for developing rating curves specifically for this often-used culvert configuration. Rating curves, or graphs showing the relationship between flow rate an inlet *head*, are the basis of culvert design, but can also be used to assess the suitability of an existing culvert. Changes in upstream hydrology or downstream channel configurations may render an initially well designed culvert inadequate. Culvert failures can be the result of slow deterioration over time, or may occur under extreme flow events (Figure 1). The template documented herein should be a valuable tool in the culvert repair and replacement decision making process. The discharge relationships that have been encoded in the worksheet can be found in Bodhaine, G. L. 1967. This USGS publication was developed to provide scientists with methods to estimate flow in culverts based on inlet and outlet head. As such, the report has very detailed discharge coefficients based on physical descriptions of the culvert.

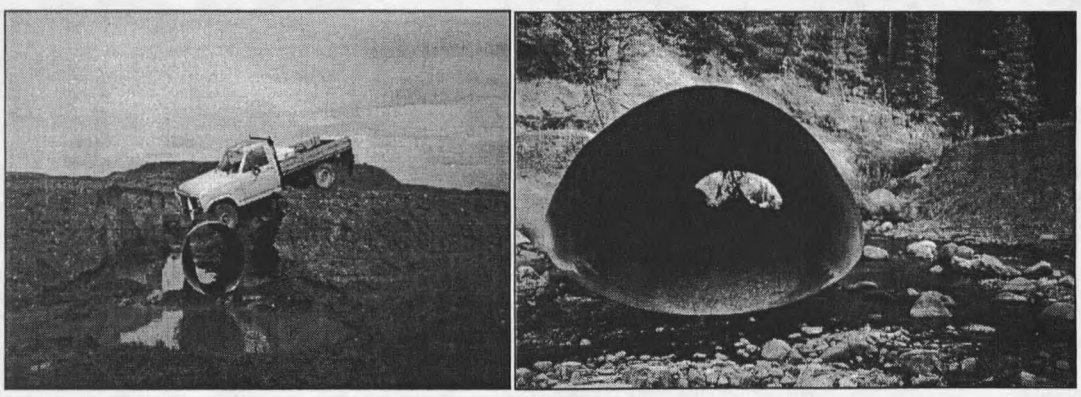


Figure 1. Culverts that failed during extreme flows.

Flow Types

Flow profiles in culverts are difficult to calculate because the flow *control* changes as the culvert fills. There are six commonly occurring flow types, as shown in Figure 2 (Bodhaine, 1967). *Low flows* are those that do not submerge the weir inlet. At some low flows the inlet itself may act as a weir (Flow Type 1), with water passing through the *critical depth* at the inlet. In culverts that are less steep, the critical depth may be at the outlet (Flow Type 2). Or, flow in the culvert may be tranquil throughout so that the control is essentially the friction loss in the culvert barrel (Flow Type 3). *High flows* occur when the inlet is submerged. If the outlet is also submerged (Flow Type 4) then the culvert acts as a pressurized pipe. In some cases the inlet may act as an orifice (Flow Type 5). Some high flow culverts may flow as a pressurized pipe but with a free-fall at the outlet (Flow Type 6). There are two more types of flow, both having a hydraulic jump in the culvert (Chanson, 1999) but these occur infrequently enough that they are excluded here.

The flow equations in Figure 2 result from writing the *energy equation* between a control section and a location of known head (the outlet head, usually). The flow equations depend on the flow rate, the inlet and exit conditions, and the shape, slope, roughness and length of the culvert. Note that the flow equations can be solved explicitly for flow rate, Q, only if the flow is Type 4 or 5, For all other flow types the equations are implicit in Q and must be solved numerically.

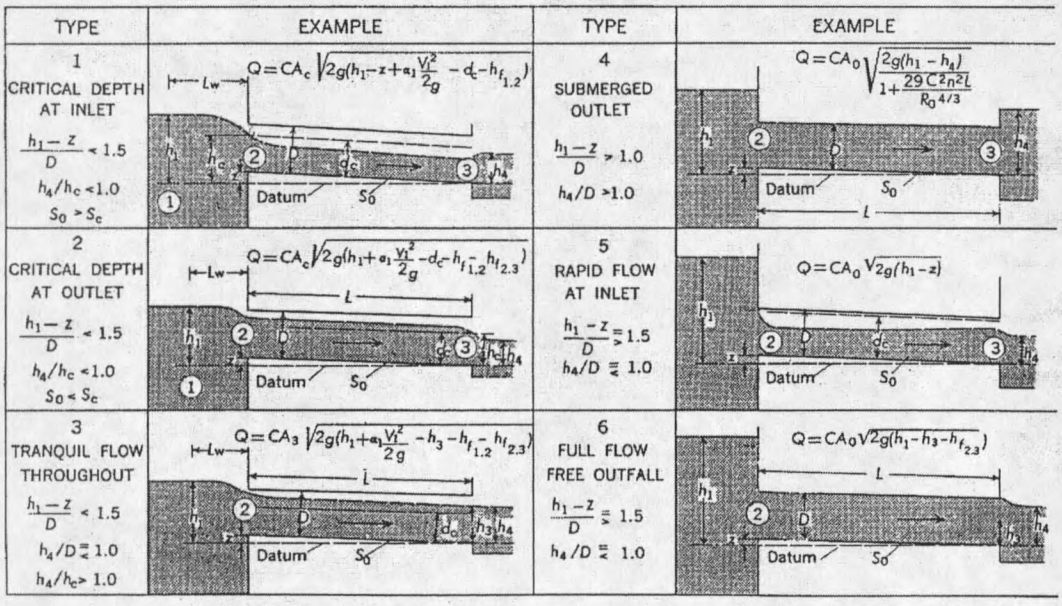


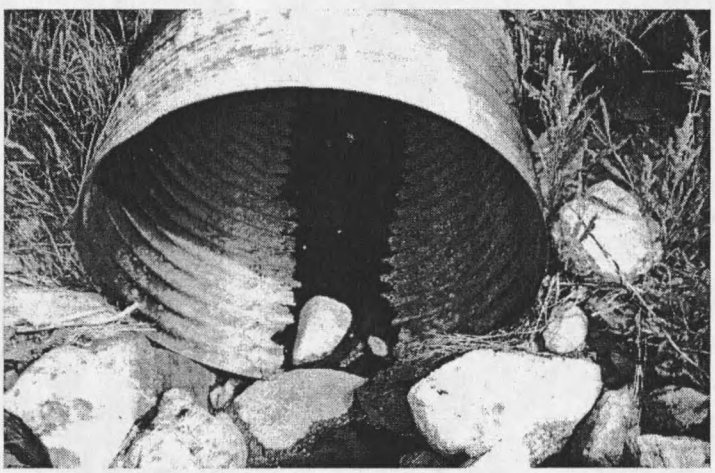
Figure 2. Classification of flow (Bodhaine, 1967).

Materials and Entrance Conditions

Culverts can be constructed from a variety of materials (concrete, steel, bricks...) and in a variety of shapes (circular, box, arch...). The presentation here considers only culverts made of corrugated steel (*Manning's n* = 0.024) with circular cross sections. There are also many different entrances that can be incorporated into the variety of culvert shapes and materials. Here we will limit discussion to only the following commonly occurring entrances:

Entrance 3 - the culvert is flush with a vertical head wall or with wingwalls.
Entrance 6 - the entrance projects into the entrance channel.
Entrance 7 - the culvert is mitered flush with a sloping embankment.

Examples of entrance conditions are shown in Figure 3. The value of the *coefficient of discharge* (C in the equations of Figure 2) is a function of the type of entrance. For some flow types, the coefficient of discharge also depends on inlet head – further complicating the implicit solution of flow rate for any given inlet head. All of the appropriate tables and graphs of Bodhaine, 1967 have been encoded into automated interpolation tables in the template.





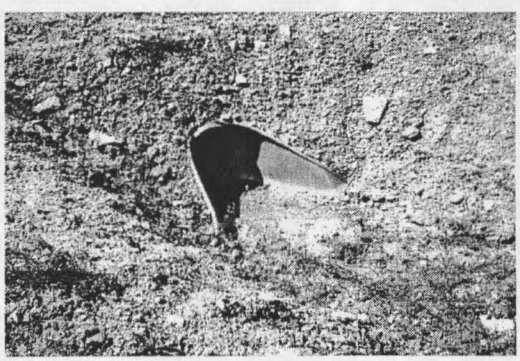


Figure 3. Entrance conditions.

Entrance Channel

Flow types 1, 2 and 3 also depend slightly on the characteristics of the inlet channel. Flow types 4, 5, and 6 are independent of the geometry and conditions of the stream as it approaches the culvert but depend heavily on the characteristics of the culvert entrance. As such, the template requires the user to provide a simple symmetric trapezoidal description of the entrance channel. An example of a trapezoidal approximation to an irregular channel is shown in Figure 4.

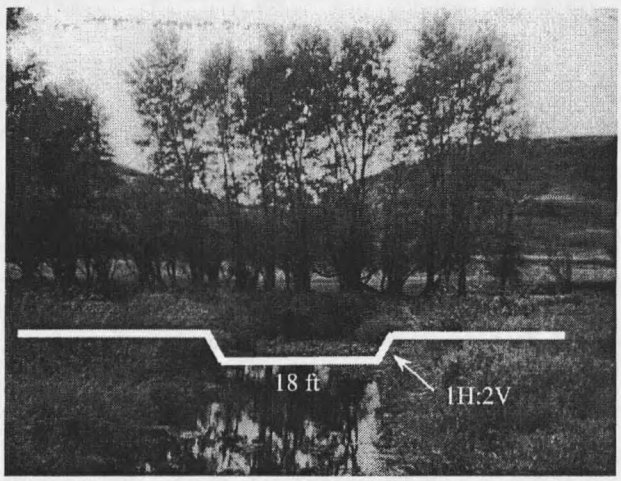


Figure 4. Trapezoidal approximation to an irregular inlet channel.

The trapezoidal approximation shown in Figure 4 would suffice for flows that are expected to remain in the channel. If extreme flows are of interest and these larger flow rates would inundate the *overbank*, the trapezoidal channel should be expanded to show the ponded conditions. An easy way to accomplish this is to keep the base width of the primary channel, but change the side slope to very gradually ascend from the main channel floor to the maximum flow depth over the overbank. Then adjust the value Manning's n to represent the dominant roughness of the overbank.

Exit Channel

The only feature of the exit channel that influence the rating curve for a culvert is the exit head. In general, there are two cases of exit conditions. If the culvert *invert* at the outlet is sufficiently above the exit channel to prohibit exit channel backwater from interfering, enter a value of zero into the template for *tail water* depth. This insures type 2 flow for low flows and type 5 or 6 flow for high flows. If the tail water will interfere, external calculations of gradually varied flow in the exit channel will lead to the proper tail water depth.

Limitations

This template is intended for use by persons that have some experience in open channel hydraulics and culvert design and are comfortable using Excel or a compatible spreadsheet. It is likely that there are combinations of input values that will result in errors rather than answers. Fortunately, it is also likely that these combinations do not often exist. For example, if the user enters a tail water depth that inundates the outlet of the culvert but is at an elevation lower than the *soffit* at the inlet end (a very long, very steep culvert), the program will assume Type 4 flow. In reality, this is likely Type 1 flow with a *hydraulic jump* inside the culvert, a case the template will not handle. In a few cases, red colored text will appear on the input page when unusual settings are entered. For example, if the user indicates that the tail water depth is higher than the road deck, a message occurs. Do not expect successful completion of the solution process if warning text occurs. There are also some general limitations that the user should be aware of:

- The template is written for circular-shaped corrugated-metal-pipe culverts only.
- The template is not recommended for culverts greater than 6 feet in diameter. A solution is possible for larger culverts, but these tend to flow as Type 3 over a wide range of flow rates. A more appropriate solution for large culverts can be arrived at using HEC-RAS (U.S. Army Corps of Engineers, 1998).
- The coefficients of discharge used here are for single culverts. Exercise caution if modeling multiple culverts in parallel.
- The code will not correctly deal with culverts having adverse sloped barrels.

Input to the Template

To use the template, the user is required to enter eleven values, at most. If the default value in the template will suffice, the user need not re-enter the value. Prior to running the calculations the template must show correct values of:

a) the culvert diameter, in feet,
b) the culvert length, in feet
c) the downstream slope of the culvert, in feet/feet,
d) if the culvert projects into the entrance channel, the length of projection, in feet,
e) the elevation of the road deck, in feet,
f) the width of the trapezoidal entrance channel, in feet,
g) the side slope (horizontal/vertical) of the entrance channel, in feet/feet,
h) the value of Manning's n for the entrance channel
i) the downstream slope of the entrance channel, in feet/feet,
j) the tail water depth, in feet, and
k) the entrance case, 3, 6 or 7.

Keep in mind that all depths or elevations, items e) and j) above, are measured relative to zero datum at the culvert exit invert. After the above items are satisfactory, use the mouse to left-click the "Run" button. The updates stage-discharge curve, tabulated and graphically, will soon appear on the I/O sheet.

Interpreting Output

The output is displayed in the table and graph below the input boxes on the I/O sheet. The output is only correct, or updated, after new input if the program has been "Run" as described above. In most cases it is acceptable to interpolate between points on the graph to estimate the flow for intermediate values of inlet head. In some cases two different flow rates will be indicated for similar inlet head values. This indicates that flow may occur as two different flow types. In this case, choose the point that has the lower flow rate. Keep in mind that inlet head is measured from the zero datum at the outlet invert. So, in a sloping culvert there can be no flow until the inlet head exceeds the inlet invert elevation. Also, if the outlet is submerged, then there can be no flow until the inlet head exceeds the tail water depth at the outlet (backwards flow is not allowed).

Glossary

The terms that are italicized throughout this report are defined, for the context of culvert design and evaluation, below.

Coefficient of Discharge – An empirical adjustment to the energy equation that accounts for minor energy losses at the inlet due to turbulence, eddy currents, contraction of flow lines, etc. These energy losses are a strong function of the entrance condition or geometry, a lesser function of the inlet head, and in some cases a weak function of the extent of difference between the cross sectional flow areas of the entrance channel and the inlet to the culvert.

Control – A phenomena in the flow path that establishes the relationship between flow rate and a measure of geometry, usually flow depth. A weir, for example, is a control structure because a weir causes water to pass through the critical depth and there is a unique relationship between flow rate and the critical depth for any flow geometry.

Critical Depth – The depth at which the specific energy is minimized for a given geometry and flow rate. Specific energy is the sum of the water flow depth and the velocity head.

Energy Equation – The relationship between the energy states at two points in a flow path. Energy is comprised of the flow depth, the channel floor and the velocity head. Energy losses are those associated with friction and minor losses due to turbulence, eddy currents, contraction of flow lines, etc. In equation form the energy equation written from a point labeled "1" to a downstream point labeled "2" occurs as:

$$y_1 + z_1 + V_1^2/2g = y_2 + z_2 + V_2^2/2g + h_m + h_l$$

where: y_1, y_2 = the flow depth s at points 1 and 2, (feet)
z_1, z_2 = the elevation of the channel invert at points 1 and 2 (feet),
V_1, V_2 = the mean flow velocity at points 1 and 2 (ft/sec),
g = the gravitational constant, 32.2 ft/sec^2,
h_m = the minor energy losses between points 1 and 2 (feet), and
h_l = the sum of all friction losses between points 1 and 2 (feet).

Head – A term that implies the energy state at any cross section. In the formal definition this includes the bed elevation, the flow depth and the velocity head. In cases where the velocity is small, the velocity head is even smaller, and that term can be ignored. This relegates the "head" at appoint to the value of the water surface elevation at that point as measured from a common datum.

High Flow – The case where the inlet end of the culvert is inundated. It turns out that the water surface at the inlet end can be a bit higher than the inlet soffit without submergence because of the contraction trajectory as flow enters the culvert. Research have used values of (h1-z)/d (the height of the water surface as measured from the inlet invert divided by the culvert diameter) ratios between 1.1 and 1.5 to define submergence. In the template, submergence is assumed to occur at (h1-z)/d = 1.4.

Hydraulic Jump – An abrupt transition from flow at a depth less than the critical depth to flow at a depth greater than the critical depth. Energy is exhausted in the hydraulic jump.

Invert - The lowest point inside the culvert.

Low Flow - The case where the inlet end of the culvert is not inundated (see High Flow). In the template, low flow occurs at (h1-z)/d < 1.4.

Manning's n – A description of the roughness of the channel surface. Larger Manning's n values indicate more resistance to flow while small values indicate a very smooth surface. The units, although rarely expressed, for Manning's n are $ft^{1/6}$. Typical values are 0.024 for corrugated metal pipe and 0.013 for smooth concrete. Complete tables of typical Manning's n values can be found in Chow, 1958.

Overbank – the portion of the channel that is outside the usual flow area and usually is inundated during extreme flow events.

Soffit – The highest point inside the culvert.

Tail Water – Water in the exit channel, immediately downstream of the culvert outlet.

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