MPC-692
June 29, 2022

Project Title

A Risk-Based Framework for Optimizing Inspection Planning of Utah Culverts

University

University of Utah

Principal Investigators

Abbas Rashidi, Ph.D.
Assistant Professor
Dept. of Civil and Environmental Engineering
University of Utah
Phone: (801) 581-3155
Email: abbas.rashidi@utah.edu
ORCID: 0000-0002-4342-0588

Research Needs

Culverts are essential assets for state departments of transportation. They facilitate the passage of surface water beneath roadways and avoid roadway disruptions (**Figure 1**). Culverts should be regularly inspected and maintained as their efficient inspection and maintenance are critical to the safe operation of transportation infrastructure systems and the prevention of human life loss, injury, or heavy financial losses. Due to the importance of this category of assets, UDOT intends to classify culverts as tier 1 assets.

Figure 1. Culvert under a road

The Utah Department of Transportation (DOT) has an inventory of over 47,000 culverts. Utah DOT management primarily responds to problems and performs maintenance on adjacent embankments. Until now, there has been no regular program for inspection or maintenance, and replacement is not scheduled on the basis of any projection of culvert service life. Utah DOT maintains some records of problem culverts, but there is no systematic program to monitor the entire inventory. The lack of historical performance data makes the specification of new culverts more difficult regarding life cycle analysis. This state of affairs suggests a problem in the near future since a significant portion of the Utah DOT culvert inventory was installed when the Interstate Highway System was built in the 1960s and 1970s and is now aging.

Management of culvert assets is an issue important to all state departments of transportation. Given the number of culverts and the potential risk of roadway disruption and property damage due to poorly maintained culverts, a systematic method to assess the condition and perform needed maintenance should be the goal of a culvert management system.

Many states, including Maine, New York, California, Pennsylvania, North Carolina, Minnesota, and Connecticut, have established pipe management systems. However, the methods used to assess culvert conditions vary widely from state to state. NCHRP Synthesis 303 reports that 37% of state DOTs have guidelines to assess pipe conditions. In these guidelines, a common practice is to classify culverts by span such that the details of the inspection change for small-diameter, midsize, and large-diameter culverts. For example, Maryland DOT classifies culverts with spans of 0 ft to 5 ft as cross-culverts and culverts with spans of 5 ft to 10 ft as struts, with different inspection criteria for each. In a similar manner, North Carolina is currently inventorying culvert assets by excluding any with spans less than 3 ft, thus significantly reducing their culvert inventory because of the typical large quantity of 2-ft-span culverts. Several states that track culvert conditions use the results of the culvert inspections to select culvert repair and rehabilitation, that is, as input to an economic decision process or a management system. However, the most common method employed to maintain culverts is to use a service-life (often called useful-life) predictor and plan some type of rehabilitation or replacement at the expiration of that service life. This method leaves significant room for improvement given the extremely imprecise nature of service-life predictions for culverts.

In 2001 the Montana DOT published the results of research conducted to determine factors that were important to evaluate the condition of a culvert. The research attempted to statistically correlate the condition of a culvert with the respective rating for each of 33 condition parameters. The study showed that only nine parameters were statistically significant with respect to the overall rating assigned by inspectors conducting the research. The nine parameters are the age of the culvert, scour at the outlet, evidence of major failure, degree of corrosion, invert of culvert worn away, sedimentation of cross-section, physical blockage, joint separation, and physical damage. Synthesis 303 indicates that most states perform culvert maintenance on an as-needed rather than preventive basis and that most do not use service-life predictions to plan rehabilitation or replacement maintenance.

While these guidelines and manuals are effective, different states considered different quantitative and qualitative parameters such as pipe shape/material/coating, drain type, installation year, highway name and etc. These guidelines are specific to each state and may not reflect Utah culverts' conditions. As a result, we plan to develop a robust system that is capable of monitoring culverts in an efficient and automated approach. This system consists of the following modules (**Figure 2**): (1) estimating the deterioration curves for UDOT culverts, (2) developing a life cycle analysis, and (3) providing a risk-based framework for assessment prioritization and inspection frequency estimation.

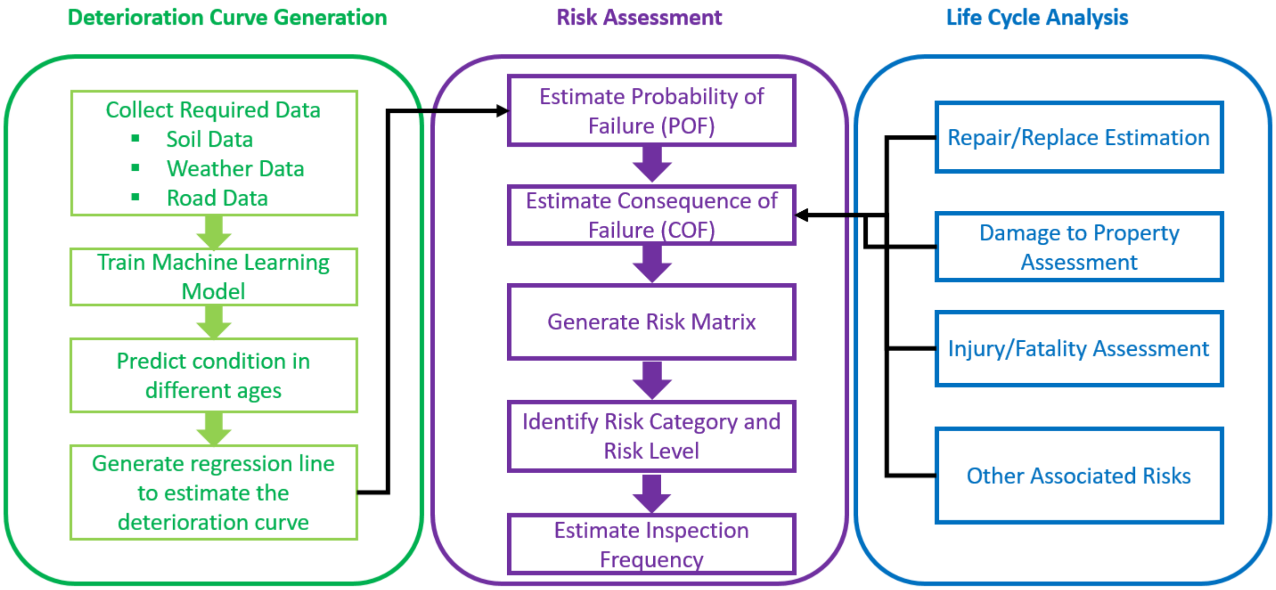

Figure 2. Framework of the life cycle analysis and risk assessment system

This project can be implemented easily, and as time passes and the datasets are being completed, the accuracy of the model will increase. Every culvert in Utah will be monitored accurately during its life cycle, and UDOT staff can predict the repair/replace date in advance. In addition, it helps in the decision-making process by identifying the most critical culverts. This system can be implemented on a GIS system to assign all the associated parameters to individual culverts to help UDOT staff find the required information efficiently. This GIS system can also be appended to the ATOM software under development by UDOT. More technical details about the proposed method will be provided within the next sections.

Research Objectives

The objective of this research project is threefold:

1) Generating deterioration curves for individual culverts to track the aging process.
2) Developing a system for life cycle analysis by considering most of the potential risks during the remaining useful life of the culvert.
3) Providing a robust platform for culvert risk assessment using deterioration curves and life cycle analysis.

Research Methods

The backbone of the project is to estimate the deterioration curve of the culverts, perform life cycle analysis, and finally develop a risk-based framework to help UDOT in decision-making. To estimate the deterioration curve of the culverts, the authors will assess the spatial and temporal characteristics of culverts. To do so, based on the geographical location and culvert material type (e.g., corrugated steel, reinforced concrete, and plastic pipes), several factors such as soil physical and chemical characteristics (e.g., soil moisture, resistivity, pH, and texture, and drainage class) and environmental conditions (e.g., flooding, live stream, and sensitive watershed), and road conditions (e.g., Annual Average Daily Traffic and pavement/cover condition) will be considered to obtain from DOTs, Web Soil Survey (WSS), Federal Emergency Management Agency's (FEMA), the

American Iron and Steel Institute (AISI), the National Corrugated Steel Pipe Association (NCSPA), and climate agencies.

Next, after completing the culvert dataset, we will use a machine learning approach to the completed culvert dataset to estimate the deterioration curves. To do so, we will train a regression model to predict the condition of a specific culvert considering its age and all the aforementioned factors. Generating the deterioration curves will assist us in estimating the failure risk using the remaining useful life of the culvert (**Figure 3**).

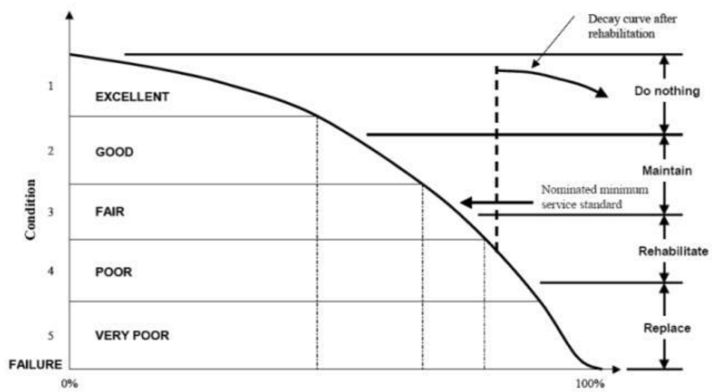

Figure 3. Sample deterioration curve for culvert [12]

In the next step, we will estimate inspection frequencies using the generated deterioration curves. Our investigations show that different States have defined different inspection frequencies, but mostly they are in the range of two to six years depending on several factors. For example, New York DOT mentioned four years, FHWA two years, Ohio DOT five years, and Indiana State suggested six years for the excellent condition, four years for the good condition, and two years for the fair condition.

However, these suggested inspection frequencies are fixed for all types of scenarios and conditions. They are not data-driven, and they are mainly based on expert judgments and historical data. In this project, we propose a risk-based framework that considers the culvert condition in estimating the inspection frequencies and reflects the risk value of potential failures in calculations.

It is common to prioritize asset inspections such as sewers, pipes, pavements, and bridges based on their risk factor. Similarly, in this project, we plan to implement a risk-based prioritization to find the most critical culverts, and based on the estimated risk factor for each culvert, we can assign inspection frequencies. The risk matrix is calculated by multiplying the Likelihood of Failure (LOF) by the Consequence of the Failure (COF) (**Equation 1**).

$$Risk = LOF \times COF \qquad \text{(Equation 1)}$$

LOF is related directly to the current condition of the culvert. As the pipes age, the failure rate increases since pipes are more susceptible to erosion and abrasion. COF is categorized into economic and social factors. Economic factors include the repair/replace estimation and damage to properties assessment. Since the real economic impact is composed of various risk factors, some studies have tried to estimate these factors using indirect approaches. For example, we can take the physical dimensions of culverts (e.g., diameter, length) to approximate the repair or replace risk factor. In addition, we can use factors such as culvert flood zone and live stream type to estimate the damage to the property risk factor. Social factors include the loss of service, which is the user delay risk factor. Similarly, we can estimate the user delay risk factor using AADT of the crossing road, the average delay per vehicle, repair/replace duration, the average rate of person-delay in dollars per hour, and vehicle occupancy factor. Finally, we can generate a risk matrix based on the probability of failure and the consequence of failure. **Figure 4** shows the risk matrix generated for 272 Utah culverts. Based on the culvert risk factor, we can assign different risk levels (i.e., Level 1, Level 2, Level 3, and Level 4) and categories (A, B, C, and Next Action). The risk category will be utilized to estimate the culvert inspection frequency. Furthermore, this procedure can be implemented and automated in a GIS system or appended to the ATOM software currently under development by UDOT. Finally, all of the associated risk factors during the culvert life cycle are included in this framework.

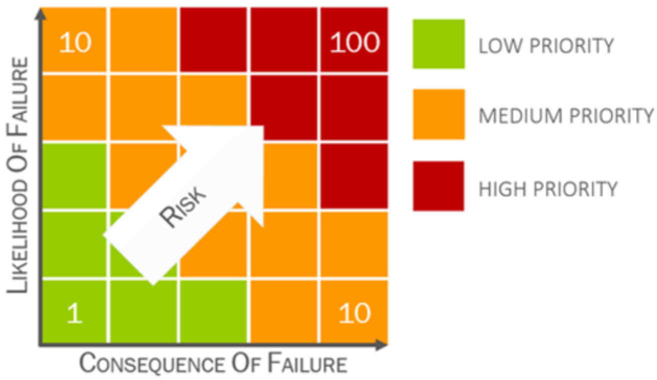

Figure 4. Sample risk matrix to prioritize critical culverts [21]

In summary, in this project, we will develop a robust system to monitor culverts' condition, and we will provide a risk-based framework for life cycle analysis. Culverts can be tracked based on the current condition and risk of failure. Most of the important life cycle risk factors are linked to the culvert and can be monitored to predict potential failures in the future. UDOT staff can repair/replace the culvert in advance and prevent high costs.

Expected Outcomes

The expected outcomes for this project will include the following items: a deterioration curve generation system, a life cycle analysis system, and a risk assessment platform on GIS/Atom. Deterioration curves will be generated specific to each culvert type and location, which will be used to predict the future conditions of a culvert. In addition, all associated risks during the culvert life cycle will be considered and estimated to better plan for potential risks in the future. Furthermore, a risk-based framework will be developed to include all of the culvert's important information, such as soil data, current condition, probability of failure, risk factors, and finally, risk level and category. This framework will be implemented on a GIS platform or on Atom software.

It is also necessary to mention that the outcomes of this project will be discussed and evaluated by UDOT personnel as the practitioners who will be benefited from this project.

Relevance to Strategic Goals

Primary strategic goal: Cost-Effective Maintenance Practices for Highway and Rail Lines

UDOT needs to develop a capital improvement project list to request the appropriate amount of funding (most likely in year 2 or 3) for optimal investment timing. In other words, recommendations for culvert inspection or rehabilitation and replacement need to be assessed and prioritized while adhering to budgetary allocations and minimizing risks and costs associated with failure. The proposed system will optimize the allocation of annual maintenance budgets by determining the culverts needing inspection and rehabilitation or replacement. At the network level, the allocation of funds is determined based upon an initial budget. Furthermore, the optimum sequential path in the annual decision-making process may be determined using a combination of operations research tools.

The system cost-effectively evaluates culvert conditions and prioritizes highway infrastructure maintenance. Also, it will estimate the minimum yearly budget requirements for a given planning horizon so that the total asset value is maintained or improved. In addition, the system can be used to make project-level decisions to inspect, rehabilitate, replace, or do nothing with limited resources.

Secondary strategic goal: Transporation Safety, Worker Safety, and Workforce Development

In the United States, approximately 40,000 lives are lost due to traffic fatalities every year. Over the years, the number of deaths on the United States' highways has even been higher than war, most diseases, and all natural disasters. Approximately one-third of all highway deaths have occurred on the roadside. More specifically, striking a culvert or a ditch is the first harmful event for more than 10 percent of the total fatal ran-off-road crashes in the United States. While these buried structures cross streams and divert water from roadways, many are in need of repair. Unexpected culvert failures can disrupt traffic, damage the environment and nearby property, and can even be fatal.

The system will eventually monitor individual culverts and identify critical old culverts under the roadway that require immediate attention. Thus, it will prevent potential injuries/fatalities associated with culvert failures under the main roads.

Educational Benefits

The PI of this project is currently teaching two relevant undergraduate and graduate-level classes called "CVEEN 6790: Advanced Computer-Aided Construction" and "CVEEN 5740: Horizontal Construction". It is expected that the developed algorithms, methods, and case studies in this project will be directly converted into new course materials for these courses. In addition, a number of selected undergraduate and graduate students will be participating in different steps of this project, including data collection, processing, and validating the obtained results.

Technology Transfer

The technology transfer process for this project will take place through three major channels: 1) publishing (presenting) research results in scholarly journals (conference proceedings); 2) direct interactions and with UDOT personnel through training sessions as the potential end-users for the results of this study, and 3) developing a GIS platform or appending the system to Atom software as the final product.

Work Plan

The project will include the following major tasks:

1) Literate review and initial evaluation of the existing risk-based management methods; Expected completion date: end of 2^{nd} month
2) Collecting culvert data to enrich the existing datasets: end of 5^{nd} month
3) Generating deterioration curves for individual culverts; Expected completion date: end of 6th month
4) Conducting a life cycle analysis; Expected completion date: end of 8th month
5) Developing a risk assessment platform; Expected completion date: end of 11th month
6) Preparing the final report; Expected completion date: end of 12th month

Project Cost

Total Project Costs:	$72,000
MPC Funds Requested:	$32,000
Matching Funds:	$40,000
Source of Matching Funds:	Utah Department of Transportation

References

[1] Arnoult, J.D. and Byrd, T., 1986. *Culvert inspection manual* (No. FHWA-IP-86-2). United States. Federal Highway Administration.

[2] Gemora, I., 2003. Pipeline assessment and certification program. In *New Pipeline Technologies, Security, and Safety* (pp. 822-825).

[3] Bowers, J.D., Magers, S.R., Pyrz, J. and Bullock, D.M., 2014. *Processes of small culvert inspection and asset management* (No. FHWA/IN/JTRP-2014/08). Purdue University. Joint Transportation Research Program.

[4] Lee, J., Park, C.Y., Baek, S., Han, S.H. and Yun, S., 2021. Risk-based prioritization of sewer pipe inspection from infrastructure asset management perspective. *Sustainability*, *13*(13), p.7213.

[5] Beaver, J.L. and McGrath, T.J., 2005. Management of Utah highway culverts. *Transportation research record*, *1904*(1), pp.113-123.

[6] Gao, C., 2019. *Use of Data Analytics and Machine Learning to Improve Culverts Asset Management Systems* (Doctoral dissertation, University of Cincinnati).

[7] Gao, C. and Elzarka, H., 2021. The use of decision tree based predictive models for improving the culvert inspection process. *Advanced Engineering Informatics*, *47*, p.101203.

[8] Hasan, M.A., 2020. *Neural Network Based Life Cycle Cost Analysis of Metal Culverts Due to Corrosion Risks in Arkansas*. Arkansas State University.

[9] Serajiantehrani, R., Najafi, M., Malek Mohammadi, M. and Kaushal, V., 2020. Framework for life-cycle cost analysis of trenchless renewal methods for large diameter culverts. In *Pipelines 2020* (pp. 309-320). Reston, VA: American Society of Civil Engineers.

[10] Piratla, K.R., Pang, W., Jin, H. and Stoner, M., 2017. *Best Practices for Assessing Culvert Health and Determining Appropriate Rehabilitation Methods* (No. FHWA-SC-17-01).

[11] Hasan, M.A., 2020. *Neural Network Based Life Cycle Cost Analysis of Metal Culverts Due to Corrosion Risks in Arkansas*. Arkansas State University.

[12] Transport Infrastructure Ireland, “Network Management – Asset Management(Pavements)”, Article, https://www.tii.ie/roads-tolling/operations-and-maintenance/Pavements/

[13] Lu, P., 2019. Investigating the life cycle costs of road culverts in difference asset management schemes.

[14] ALTarawneh, B.K., 2005. *Inspection, durability, and risk assessment of highway culverts*. Ohio University.

[15] Perrin Jr, J., Jhaveri, C.S. and Perrin Jr, J., 2004, January. The economic costs of culvert failures. In *Prepared for TRB 2004 Annual Meeting, Washington DC*.

[16] Albuquerque, F.D.B., Sicking, D.L. and Lechtenberg, K.A., 2009. *Evaluation of safety treatments for roadside culverts* (No. TRP-03-201-09). Midwest Roadside Safety Facility.

[17] Meegoda, J.N., Juliano, T.M., Ratnaweera, P. and Abdel-Malek, L., 2005. Framework for inspection, maintenance, and replacement of corrugated steel culvert pipes. *Transportation Research Record*, *1911*(1), pp.22-30.

[18] Piratla, K.R., Jin, H. and Yazdekhasti, S., 2019. A failure risk-based culvert renewal prioritization framework. *Infrastructures*, *4*(3), p.43.

[19] Tang, Y., Bao, Y., Zheng, Z., Zhang, J. and Cai, Y., 2022. Performance assessment of deteriorating reinforced concrete drainage culverts: A case study. *Engineering Failure Analysis*, *131*, p.105845.

[20] Sousa, F., Dias, S., Matos, J.C. and Camões, A., 2021, May. Development of Culvert Risk Condition Evaluation for Decision-Making Within Road Infrastructure Management. In *International Probabilistic Workshop* (pp. 265-279). Springer, Cham.

[21] Town of Carry, “Buried Infrastructure Asset Management Plan”, 2018.