Culvert Inspection to Asset Management: Climate-Change Informed Capital Works Program for Alaska Highway

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ABSTRACT

The paper outlines a comprehensive approach utilizing culvert inventory and condition data collected based on the AASHTO Culvert and Storm Drain System Inspection Guide (2020) to develop a condition, and climate-informed risk-based twenty-year capital works program for 2,200 culverts on Alaska Highway. The paper goes on to explain the methodology for establishing monetized life-cycle failure risks stemming from condition deterioration and extreme climate events. The life-cycle risk assessment is used to develop a culvert asset management system, which is used to produce a multi-year climate-informed capital works program.

In a previous study, a climate change vulnerability and risk assessment were completed on selected critical culverts on the highway using inventory and limited condition data collected 10 years earlier. As an outcome of this previous study, a comprehensive culvert inspection was carried out in 2022 based on the more robust data collection criteria outlined in the Culvert and Storm Drain System Inspection Manual (AASHTO, 2020). This 2020 AASHTO Inspection Manual, updates the inspection and rating criteria, incorporating over 30 years of changes since its original publication in 1986. The previous study's approach to assessing the risks posed by condition deterioration and climate change to 2,200 culverts along the Alaska Highway, British Columbia, was improved with more accurate culvert components-based predictive models to develop a capital works program to address those risks in terms of replacement, adaptation, and maintenance.

The adaptation and/or replacement options, (strategies), were evaluated in a Life Cycle Cost Analysis (LCCA), by monetizing the costs and benefits of multiple strategies over a 60-year period. The economic analysis for climate change adaptation options quantifies the extent of cost and benefit of adaptation options under climate change scenarios. The costs considered in the LCCA include both "direct costs," directly incurred by the asset owners, and "user costs," which road users would incur through delays and detours. Overall, this approach should ensure that the culverts along the Alaska Highway can withstand the impacts of climate change and remain functional over the next 20 years.

Keywords: Culvert Inventory and Condition Inspection, Culvert Asset Management, Transportation Asset Management, Climate Change Adaptation, Climate Vulnerability, Risk-Based Asset Management, Sustainability and Resilience, Transportation Systems Resilience, Risk and Resilience Management, Natural Hazards and Extreme Weather Events, Climate Change, Vulnerability and Resilience Assessment, Hazard Mitigation

1.0 INTRODUCTION

Tetra Tech Canada Inc. (Tetra Tech) was retained by the Public Services and Procurement Canada (PSPC) to provide engineering services to develop a culvert capital works program for the Alaska Highway km 133-968, British Columbia and Yukon. The Alaska Highway stretches 2,450 kilometres through northern BC, the Yukon, and the State of Alaska. Responsibility for the 835 km section from km 133, north of the City of Fort St. John, BC, to km 968 at the BC/Yukon border, rests with PSPC for maintenance and operations.

To develop the culvert capital works program, Tetra Tech carried out a culvert inventory and condition inspection, climate change vulnerability assessment, and developed an asset management plan. The culvert inventory and inspection utilized a set of inspection criteria and collected inventory and condition data to assess the current condition of the culverts. The climate change vulnerability assessment included analyzing climate data and developing adaptation strategies through a hydrological vulnerability assessment of all culverts.

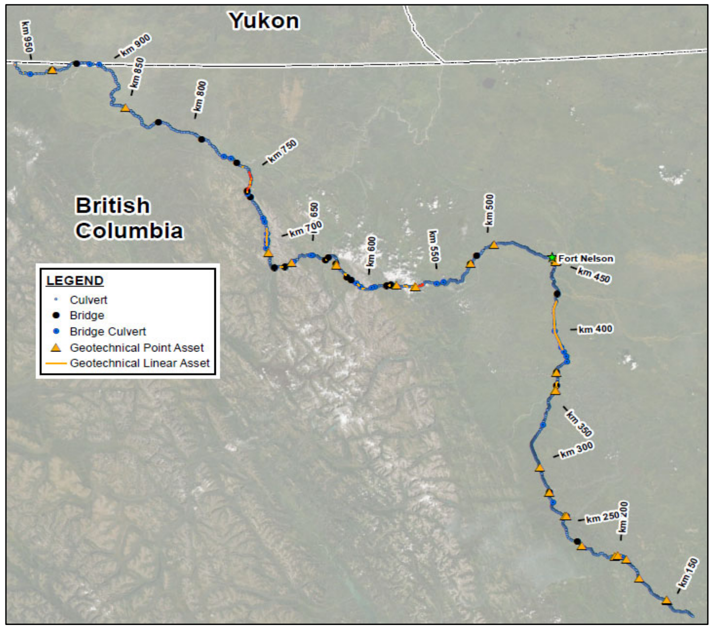

Figure 1: Infrastructure Assets within Project Limits

Based on these results, a 20-year culvert capital works program was developed through a literature review, multi-criteria decision analysis, component deterioration modelling, and a comprehensive cost-benefit economic analysis of the condition and climate resiliency-based treatments. The culvert capital works program provides a comprehensive approach to improving the condition and climate resiliency of the culverts on the Alaska Highway. Figure 1 shows the project limits.

1.1 Background

The Highway was originally built during World War II to provide land access to Alaska. Over the past decades, there has been an ongoing program to improve the original road. Sections under the BC government's and Yukon government's jurisdiction to the south and north, respectively, have been reconstructed to the standard is known as RAU-100 (rural, arterial, undivided, 100 km/h design speed).

Drainage infrastructure systems such as culverts are an essential aspect of Alaska Highway's transportation assets to maintain uninterrupted access to the remote northern communities in British Columbia. The culvert assets require routine inspection, maintenance and timely replacement to avoid traffic disruption along the Alaska Highway. Some culvert failures will result in unplanned closure and challenges to the agency because of costly emergency replacement projects or potentially high indirect user costs due to detours and traffic delays. The effective management of the culvert assets requires reliable inventory and condition data on culvert structural and geometric characteristics and culvert components conditions.

2.0 LITERATURE REVIEW

Culvert inspection has traditionally received less importance from agencies than bridges, leading to many structures with deferred maintenance and varying levels of distress that are not contained in any formal inventory database. Individual culverts cost significantly less to replace and maintain than other major assets; however, the total inventory of culverts is significant. The culvert assets are vulnerable to failure due to several factors such as age, physical damage, larger loads, environmental exposure, etc. A standardized inspection approach is required to identify the culvert problems early in life to repair the issue before total system failure, cost-effectively.

In 1986 Federal Highway Administration (FHWA) published a Culvert Inspection Manual (FHWA, 1986) supplement to the "Bridge Inspector's Training Manual," which provided a commentary on culvert structures, inspection procedures, culvert component inspection, and methodology to inspect the culverts. For a long time, it has been the only document providing a comprehensive guide to a methodology for inspecting and rating culverts and their components. It also provides a numerical condition rating criterion for culverts on a scale of 0 to 9; similarly, a maintenance rating scale was also provided.

In 2016, under NCHRP 14-26, research was conducted to develop an inspection manual, primarily through an update of the 1986 FHWA manual, for accessing the condition of the in-service culvert and storm drain systems. In 2020, the Culvert and Storm Drain System Inspection Manual (AASHTO, 2020) was published as the final deliverable of the NCHRP 14-26 project. The manual addresses the need to collect inventory, quantify, and rate the condition of in-service culverts and to update the inspection and rating criteria incorporating over 30 years of change since its original publication in 1986. Culvert inventory and condition inspection were carried out based on the data collection criteria documented in the published Guide and the customized parameters based on reviewing previously gathered information.

The culvert assets need effective maintenance, rehabilitation, and replacement over time to maintain the network condition and value. Like other major highway systems, Alaska Highway is vulnerable to unexpected culvert failures. The culvert failures occasionally result in embankment washout and occasional loss of life. The failures result in unexpectedly high costs to the agency and public (in terms of time and resources) using the Highway. Therefore, drainage infrastructure systems are in need of special attention in terms of a proactive/preventive asset management strategy.

US Army Corps of Engineers, American Association of State Highway and Transportation Officials (AASHTO), and ASTM have made recommendations to help agencies select culvert pipes, but each agency also assumes its own life expectancy based on environment and experience.

In 2004, transportation agencies across the United States and Canada were surveyed regarding culvert failures and Life Cycle Cost Analysis (LCCA) issues such as replacement cost and user delay cost (Joseph Perrin Jr., 2004) The study concludes with the importance of having a tracking system to identify the cause of culvert failures and quantify the associated costs.

In 2006, ODOT statewide culvert asset management aimed to reduce the risk of structural failure of culverts that serve major highways (Joseph Perrin Jr., 2004). The study validated previous studies that plate type, culvert age, drainage water pH, flow abrasiveness, and flow velocity all contributed to the deterioration of metal culverts. The proposed risk assessment approach used a modifier based on the ratio of soil cover (H) to culvert rise (R) to adjust the average culvert rating. The proposed modifier indirectly considers the consequences of failure, in terms that immediate risk to vehicles will be higher for a culvert with a low H/R ratio than when with a high H/R fails.

In 2008, Midwest Regional University Transportation Center researchers developed field protocols and operational business rules for inventory data collection, frequency of inspection, and analysis and reporting mechanisms (Mohammad Najafi, 2008) The condition assessment protocol developed can be used to evaluate the overall condition of the culverts and can be used for decision-making regarding the repair, renewal or replacement of culverts.

The literature highlights the importance of effective maintenance, rehabilitation, and replacement of drainage infrastructure assets, particularly culverts, to maintain network condition and value. The deterioration of culverts can lead to reduced service levels, increased maintenance costs, and ultimately deterioration of the transportation system. Unexpected culvert failures can result in embankment washout and occasional loss of life, leading to high costs to the agency and the public.

3.0 METHODOLOGY

The Vulnerability Assessment of Alaska Highway culverts was carried out using the methodology documented under the Vulnerability Assessment and Adaptation Framework (FHWA, 2017) (the Framework) by FHWA.

The vulnerability assessment methodology used in this study is similar to Infrastructure Vulnerability and Risk Assessment due to Changing Climate and Extreme Weather Events (Michel, Waseem, Frame, Miguez, & Moschini, 2022).

The Framework provides an in-depth and structured process for assessing the infrastructure assets' vulnerability. The adopted methodology consisted of the following:

- Objectives and Scope;
- Inventory and Condition Data;
- Climate Data and Hydrologic Analysis;
- Vulnerability Assessment;
- Treatments and Adaptation Options;
- Analysis and Prioritization; and
- Capital Works Program.

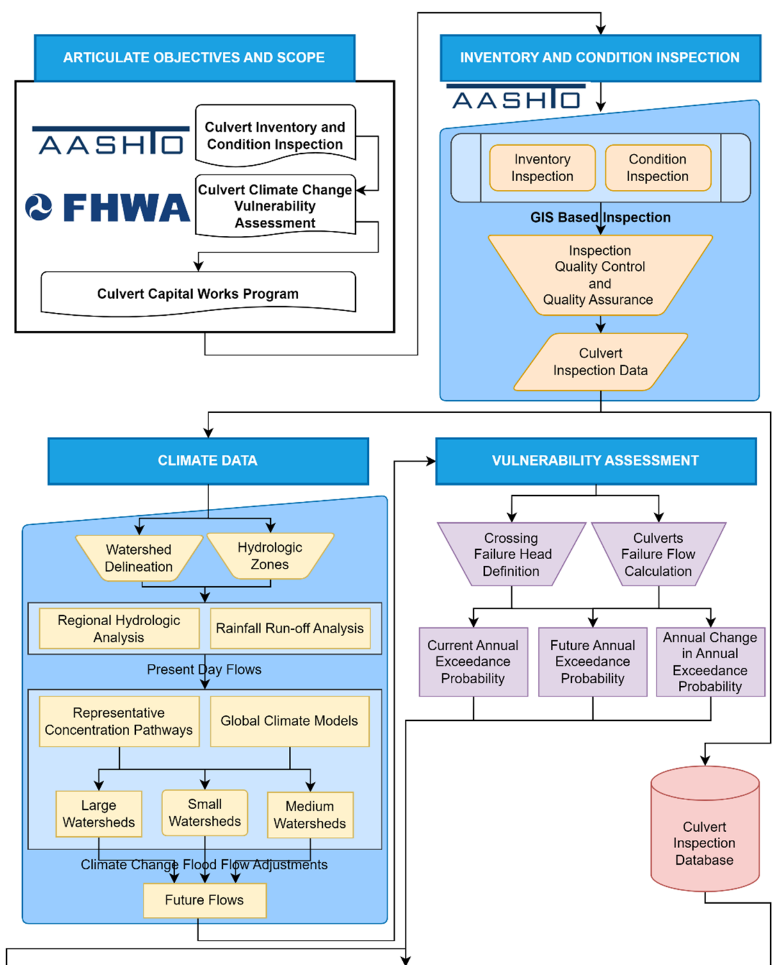

Figure 2: Culvert Inspection to Climate-Change Informed Capital Works Program Flowchart

Figure 2 and Figure 3 show the culvert inspection to climate-change informed capital works program methodology flowchart.

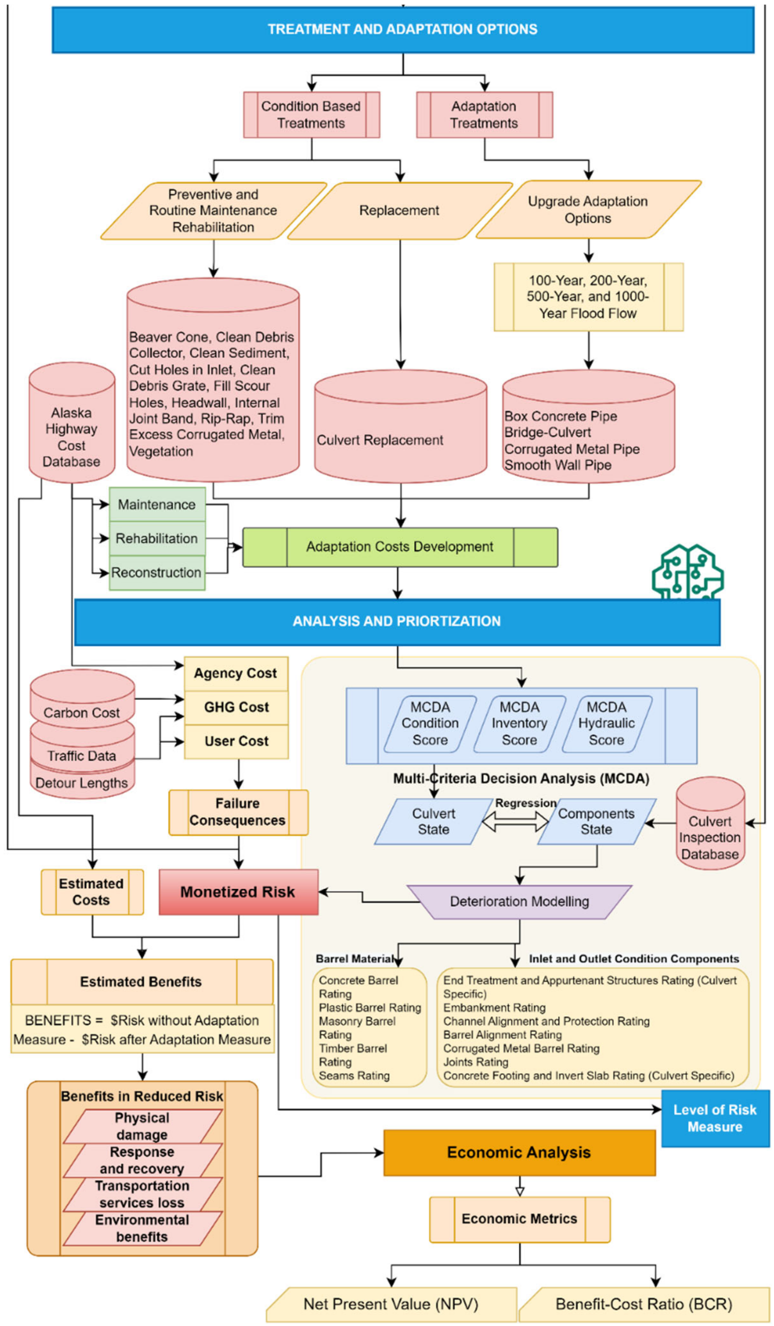

Figure 3: Culvert Inspection to Climate-Change Informed Capital Works Program Flowchart

4.0 OBJECTIVE AND SCOPE

This study aimed to collect culvert inventory and inspection data and then use the data to create a comprehensive culvert capital works program. In addition, the study sought to determine which culverts may be prone to climate and weather-related vulnerabilities. By analyzing the condition of the culverts and identifying potentially vulnerable culverts, PSPC were able to prioritize actions and strategies that could improve the overall condition of the culvert network and increase their resilience and adaptability in the face of a changing climate. The resulting culvert capital works program and vulnerability assessments serve as a valuable resource for PSPC as they work to maintain and enhance the culvert network.

The capital work program intends to develop a listing of culverts prioritized for replacement/upgrades, which will serve as a guide to prepare future improvement packages (standalone tender or packaged with other reconstruction) in a sequence that reduces the risk of culvert failure(s) damaging the highway. Where possible, culverts should be prioritized and bundled considering PSPC's capital budgets and construction implementation to complete the work most efficiently and economically.

The following were the primary objectives of the project:

- Background Information and Inspection Data Review
- Culvert Condition Modelling Application Development
- Culvert Components Deterioration Models

- Culvert Components Treatments
- Climate Change Vulnerability Assessment
- Risk Assessment Framework
- Treatment Selection and Decisions Framework

4.1 Evaluation of Culverts Criticality

The criticality of culverts was evaluated using multiple criteria as follows:

- Overall and component condition as collected in the 2021 Condition and Inventory Inspection Survey;
- Geometric and physical characteristics collected during the inventory inspection survey;
- Hydraulic capacity of culvert and demands based on hydraulic analysis;
- Owner consequences as a result of the failure;
- Length and duration of a detour route in the event of failure;
- Immediate, direct and substantial disruption to the transportation system by quantifying the user consequence of the failure;
- Use/operation of each link or node on the highway. Highly used (in terms of traffic) connections are considered more important than lesser-used segments;
- Provide access and connections to major cities along the highway at the City of Watson Lake, the City of Fort Nelson, and the City of Fort St. John; and
- Taking account of the extreme weather vulnerabilities of the asset due to climate change.

4.1.1 Condition

Around 2,139 culverts service the Alaska Highway throughout the 835 km section from km 133, north of Fort St. John, BC, to km 968 at the BC/Yukon border. All inventoried culverts were modeled to establish a probability of structural failure due to ongoing condition deterioration.

4.1.2 Climate Change Adaptation

The criteria were established to select the culvert crossings for evaluation for applicable climate change adaptation treatments. The culverts were selected based on the following criteria among all the culverts that required capacity upgrade to meet the increased flow demand in 2080 due to climate change:

- Culverts crossing the main alignment of Alaska Highway were included or excluded based on the following;
  - Including all culverts with an equivalent diameter ≥ 900 mm (183 Culverts);
  - Including all culverts with equivalent diameter < 900 mm and having a predicted existing culvert's failure flow return period of fewer than 100 years in the next 20 years. (Maximum 45 Culverts)
  - Including all Installed alongside one or more other culverts; and
  - Excluding culverts with equivalent diameter ≤ 600 mm and embankment cover ≤ 2,000 mm;

Culverts parallel to the highway along the ditch and crossing sideroad/access roads were excluded from the climate-based assessment. The climate resiliency-related criteria allowed the selection of 228 culvert crossings for flow analysis, 10.6% of total culverts in the inventory.

These were either the larger crossings along the highway with defined watercourses having potential for failure during flood flow, smaller diameter culverts installed in high embankments with longer spans and low return periods and installed alongside one or more other culverts. The selected culverts are likely the most expensive to repair in case of failure.

The inclusion of smaller culverts under deep embankments was done to account for the risk of culvert blockage and possible headwater buildup leading to piping failures. Deep culverts are difficult to reach and maintain. A small amount of debris can easily block the inlet end of a culvert and promote a deep pool's formation, adding porewater pressure through the road embankment. This, in turn, can promote piping failures. In summary, the selection was based on the consequence of failure and the associated costs needed to re-open the highway to public traffic.

5.0 INVENTORY AND CONDITION DATA

Alaska Highway culvert data collection criteria were developed based on AASHTO Culvert and Storm Drain System Inspection Guide (2020) and the previous culvert inspection review. Figure 4 shows the AASHTO Culvert and Storm Drain System Inspection Guide (2020). Complete details of the comprehensive culvert inventory and inspection procedure are provided in the paper titled Streamlining Culvert Inspection: A Tablet-based Inventory and Condition Inspection System for Asset Management (Waseem & Michel, 2023).

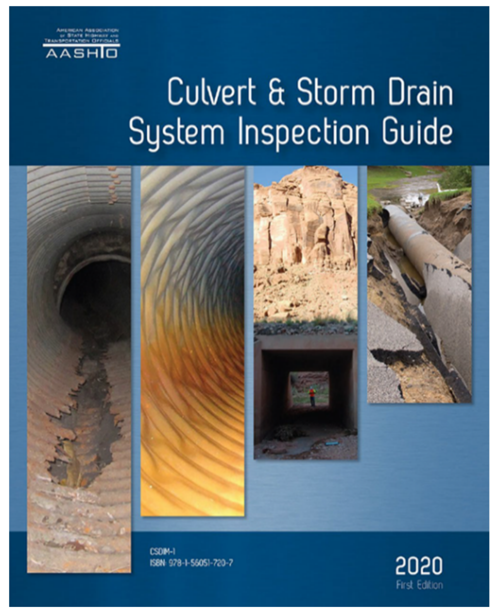

Figure 4: AASHTO Culvert and Storm Drain System Inspection Guide (2020)

The inspection team reviewed the 2010 and 2011 inspection inventory and gathered data, locations, and condition ratings. Then the team developed the data collection criteria for the current culvert inventory and condition inspection.

Culvert Inspection consists of a collection of two types of data:

- **Inventory:** The inspection involves verifying and updating the existing culvert database locations, culvert type, geometry, inlet and outlet-specific information. The inventory inspection also included the addition of new or missing culverts in the existing inventory and the identification of culverts in the existing inventory that do not exist anymore.
- **Condition:** The inspection consists of a visual assessment and condition rating of individual culvert components, such as approach roadway, embankment, channel, end treatments, appurtenant structures, barrel alignment, barrel, joins, and seams.

The culvert inspection involved rating the condition of the individual components of the culvert system. The condition of components was assessed for the culvert's structural integrity, hydraulic performance, and roadside compatibility.

The field inspection was carried out by trained inspectors using the ArcGIS based Field Maps application on a tablet. ArcGIS Field Maps™ is an all-in-one app that uses data-driven maps to help mobile workers collect and edit data, find assets and information, and report their real-time locations. ArcGIS Field Maps™ application collected culvert inlet, outlet locations, culvert inventory data, culvert condition data, and culvert imagery.

A quality management program was implemented during the field data collection and post-data collection to maintain an appropriate level of quality. The quality management program consisted of the following: A quality control person was assigned to oversee the quality of the data collection. The quality management program consisted of quality control procedures, which were reviewed and approved by the project manager. The quality control procedures were implemented during the field data collection and were monitored during the data collection.

6.0 CLIMATE DATA AND HYDROLOGIC ANALYSIS

Changes in climate will have a profound effect on the hydrology of the watercourses crossing the Alaska Highway. The hydrologic analysis was undertaken to develop flood flow estimates for each selected drainage assets across a range of return periods (2-year to 1000-year) for all years between 2020 and 2080. The climate data and hydrologic analysis is based on the previous study (Michel, Waseem, Frame, Miguez, & Moschini, 2022).

The subject watersheds vary greatly in size, from several hectares up to thousands of square kilometres. Given the large range of areas, a variety of governing flood mechanisms are expected across the subject watersheds. Small watersheds generally have their flood flows governed by an intense summer rain event, while flood flows of large watersheds will be governed by freshet snowmelt, and middling watershed areas can be governed by either, or a combination of the two (rain-on-snow). To accommodate the range of hydrologic regimes two different methods were used:

- A regional hydrologic analysis (for the larger watersheds); and
- A rainfall-runoff analysis (for the smaller watersheds).

Watershed areas of the 1790 crossings were delineated utilizing 1:50,000 NTS data. Preliminary delineations were completed from a digital elevation model (DEM) through watershed delineation algorithms available in the software ArcMap 10.8.2. Each watershed area was then further refined manually to include additional drainage areas likely to contribute to the subject culverts (i.e., roadside ditches not captured by the NTS DEM).

With a length of 835 kilometers, the study area of the Alaska Highway alignment traverses a variety of terrains, each with unique physiographic characteristics and hydrologic behaviours. In order to account for these changes in physiographic settings the Highway was broken down into five hydrologic "zones", each of which is expected to generate relatively homogeneous hydrologic responses. The flood hydrology of each zone was evaluated separately, with the resulting flood flow rates being homogenously applied to all subject watercourse crossings within the zone. Figure 5 shows the five hydrological sectors.

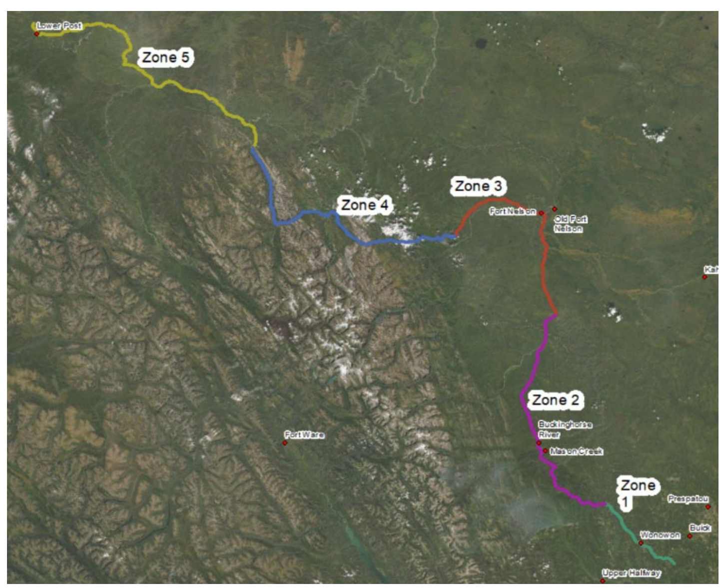

Figure 5: Hydrological Sectors

Adjustments were made to the flood flow calculations to reflect anticipated changes in hydrology for the Year 2080 due to climate change. A hybrid approach utilizing two separate methods was employed to depict the nuances in climate change effects on both small and large watersheds.

Representative Concentration Pathways (RCPs) are global greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC) to be used in assessing future climate. Each pathway describes different climate change futures, each of which is considered possible depending on the level of greenhouse gases emission in years to come.

Pacific Climate Impacts Consortium (PCIC) provides downscaled projections from over two dozen GCMs. Flood flow estimates for large watersheds were adjusted for the expected effects of climate change through the use of PCIC: Station Hydrologic Model Output data. This dataset provides simulated streamflow data for various watercourses throughout British Columbia where WSC gauges are installed Flood flow estimates for small watersheds, which had initially been estimated through rainfall-runoff modelling, was updated for the Year 2080 by remodeling the catchments with projected rainfall depths for regional storms in the year 2080.

7.0 VULNERABILITY ASSESSMENT

The vulnerability of transportation assets to climate change is intricately related to the asset's or system's **exposure**, **sensitivity,** and/or **adaptive capacity** to the effects of climate.

- **Exposure** refers to whether an asset or system is located in an area experiencing the direct effects of climate change;
- **Sensitivity** refers to how the asset or system fares when exposed to climate variability; and
- **Adaptive** capacity refers to the system's ability to cope/respond to climate variability or future climate impacts.

In order to assess the vulnerability, the team used climate, and extreme weather variables developed to identify and evaluate the exposure, sensitivity, and adaptive capacity of the system to determine its vulnerability to extreme weather and climate change. Risk, which considers the probability that an asset will experience a particular impact and the severity or consequence of the impact, was also incorporated when assessing vulnerability.

We used the Engineering Informed Assessment methodology for culverts. **Engineering-informed assessment** is characterized by a greater level of asset-specific data and analysis. Tetra Tech used an in-house engineering-informed assessment approach for the vulnerability assessment of assets. The in-house assessment approach (St. Michel, Reggin, & Leung, 2017) is based on the US Army Corps of Engineers published guide (USACE, 2011) covering risk and reliability-based engineering. The selected assessment approach is referred to as risk and Life Cycle Cost Analysis (LCCA).

The hydrotechnical portion of this assessment aimed at quantifying the flood flow magnitudes at each of the evaluated watercourse crossings. Flows were estimated for both present-day and future projections capturing the anticipated effects of climate change. These flows were then used to evaluate the hydraulic performance of the existing culverts. The risk was then quantified by comparing the magnitudes of flood flows to the capacity of the crossing.

7.1 Calculating Risk

Risk is defined by the International Standards Organization (ISO) as the effect of uncertainty on objectives and is expressed in terms of the likelihood of occurrence of an asset failure and the consequence of damage given such an event. The United States Army Corps of Engineers (USACE, 2011) guide to risk and reliability based engineering as related to civil structures uses the same generally accepted definition of risk as to the product of the probability of an event happening and the economic consequences of the event.

$$\$Risk = [P(Design\ Event\ Occurrence) + P(Structural\ Failure)]x\ \$Consequence \quad (1)$$

Where:

$\boldsymbol{P(Design\ Event\ Occurrence)}$ is the probability of failure of asset due to design event occurrence.

$\boldsymbol{P(Structural\ Failure)}$ is the probability of structural failure, e.g., collapse due to the ageing factors such as corrosion for culverts etc.

$\$\boldsymbol{Consequence}$ is the monitory value of the loss in terms of direct cost to the owner and cost to the road users in the event of failure of due to any of the failure mechanisms. The USACE methodology applies the concept of monetizing the consequences of unsatisfactory performance, placing a financial value on the economy for such things as loss of use.

The reliability is defined as the probability of loading demand remaining less than structural capacity in any given year of a structure's life. The USACE guide expresses the reliability of a structure in terms of the inverse of its Probability of Unsatisfactory Performance (PUP). The PUP is typically near zero when a structure is new and approaches unity when the demand is expected to exceed capacity.

The $Risk is defined as the risk expressed in the cost of the consequences ($Consequences) multiplied by PUP in a given year. If the $Risk is greater than the rehabilitation project's financial cost, it can be financially justified. Quantifying the $Risk of the unsatisfactory performance of the culvert system and subsequent reduction of $Risk monetarily as a result of a strategy compared to doing nothing, i.e. not rehabilitating the site, has been determined to establish a prioritization between the various identified strategies.

This study assumed all drainage infrastructure is vulnerable to failure in one of two ways; either through failure to accommodate a flood flow in any given year or a failure of material due to corrosion/age. Therefore, the overall PUP for each piece of drainage infrastructure was calculated based on the joint probability of either failure method arising in any given year.

The probability of flood failure for each culvert crossing was determined by comparing the failure flow calculated for the crossing to the flood return probabilities that had been developed for that watercourse. Each culvert's vulnerability to encounter a catastrophic material failure was estimated based on the 2021 condition inspection of culverts. Table 1 shows the culvert structural probability of unsatisfactory performance for each condition state of any given culvert.

Table 1: Culvert Structural Annual Probability of Unsatisfactory Performance

Condition State	Condition	Age	Annual Probability of Unsatisfactory Performance
1	Excellent	1	0.1%
2	Good	41	0.5%
3	Fair	61	2.0%
4	Poor	71	5.0%

5	Severe	76	10.0%

In each subsequent year, the P_{UP} is estimated using the developed equation below:

$$P_{UP} = Min(0.1, 0.004\, e^{1.1513\ x\ Culvert\ State}) \quad (2)$$

Culvert State = Overall culvert condition from 1 to 5 obtained from regression Equation

The equation limits the maximum additional annual structural probability to 10% to keep the total monetized risk during the service life below the replacement cost. Figure 6 shows the PUP by culvert state.

Lifespan expectancies for culverts will vary considerably depending on the chemistry of the soils and water they are exposed to.

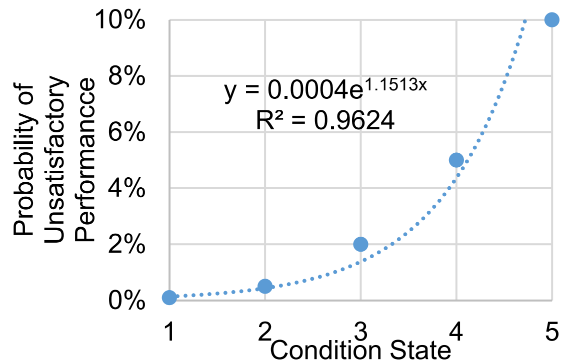

Figure 6: PUP by Culvert State

8.0 TREATMENTS AND ADAPTATION OPTIONS

Culvert maintenance or preservation activities can be categorized as emergency maintenance, preventive maintenance, routine maintenance, rehabilitation and replacement.

- **Emergency maintenance:** Activities taken in response to unforeseen events that affect culvert performance (Mohammad Najafi, 2008).
- **Preventive maintenance:** Activities that aim to prevent more serious problems in the future (Mohammad Najafi, 2008). Typical activities include joint sealing, concrete patching, mortar repair, invert paving, scour prevention, and ditch cleaning and repair.
- **Routine maintenance:** Scheduled activities that aim to maintain the culvert in working condition by addressing deterioration issues. For example, during the scheduled maintenance, the entire drainage structure is inspected to define maintenance activities. Routine maintenance includes work such as cleaning, debris removal, and realignment. "If the routine maintenance activities are not enough to solve a problem in a culvert and replacement is not a feasible option, then some of the repair techniques should be employed" (Mohammad Najafi, 2008).
- **Rehabilitation**: Activities that restore a culvert's condition to its initial state and renew the culvert service life (Mohammad Najafi, 2008). Rehabilitation methods include repair of basically sound end walls and wing walls, invert paving, repair of scour, slope stabilization, streambed paving, the addition of an apron or cut-off wall, improving the inlet configuration to enhance culvert performance, or installing debris collectors", as well as slip lining, cured-in-place pipes, and pipe bursting (Mohammad Najafi, 2008).
- **Replacement:** Replacing an existing culvert with a new one, usually by cutting it open or using a trenchless method (Bruce D. Wagener, 2014). This work is considered a Capital expense and is, therefore, the focus of this report.

In the study preventive maintenance, routine maintenance, and rehabilitation were grouped together under the assumption these treatments will be done in the same given year. The replacement treatments were divided into two types one due to the end of service life due to severe condition of the culvert, and a second where the replacement is done due to the adaptation of the existing culvert crossing. The replacement strategy due to the end of service life was applied when the culverts forecasted service life ended. Table 2 provides the type and list of condition-based treatments considered in the analysis.

Table 2: Condition-based Treatments

Type	Treatments	
Preventive Maintenance, Routine Maintenance and Rehabilitation	▪ **Beaver Cone** ▪ **Clean Debris Collector** ▪ **Clean Sediment** ▪ **Cut Holes in Inlet** ▪ **Clean Debris Grate** ▪ **Fill Scour Holes**	▪ **Headwall** ▪ **Internal Joint Band** ▪ **Rip-Rap** ▪ **Trim Excess Corrugated Metal** ▪ **Vegetation**
End-of-service life replacement due to severe condition	▪ **Culvert Replacement** – Minimum Construction Cost of Open-Cut and Trenchless Methods	

The adaptation treatment for culverts consists of upgrading the flow capacity with larger size single or multiple culverts or for larger flows, replacing them with a bridge-culvert. The upgrade strategies are applicable due to climate change when the 2080 flow exceeds the existing culvert capacity at a site.

Culverts which will require a diameter larger than 2.7 m are assumed to be replaced with a bridge-culvert, while the smaller culverts are assumed to be replaced with a conventional culvert. Conventional culverts, were assigned either an open-cut or trenchless installation based on the lowest construction costs.

9.0 ANALYSIS AND PRIORITIZATION

Multiple criteria or multicriteria decision analysis (MCDA) – also known as multiple-criteria decision-making (MCDM) – is the collective name of formal approaches that support decision-making by taking into account multiple criteria in an explicit and transparent way (Belton V, 2002).

Multi-criteria decision analysis (MCDA) is a powerful tool for evaluating infrastructure projects. It enables decision-makers to identify and compare the relative merits of alternative projects and assess the impact of uncertainty, and incorporate designers' preferences. MCDA has been increasingly used in the last decade for evaluating infrastructure projects.

MCDA is a systematic process used for analyzing discrete decision problems where the circumstances are not clearly defined. MCDA is based on the concept of deriving an overall score for the decision option, or alternative, being analyzed. The decision maker defines the relative importance factors of criteria as they pertain to a specific project. Relative importance factors are numerical representations of the preference of the decision maker, commonly based on background information and experience. MCDA provides a numerical score, or rating, assigned to a given alternative with respect to each criterion.

In decision-making scenarios, there may exist disagreement between varying decision makers as to the relative importance given to criteria. It is possible, with MCDA techniques, to quickly examine many scenarios and provide simple tools for comparison.

A simple linear additive model takes the following form:

$$P_j = \sum_{i=1}^{n} w_i \, s_{ij} \tag{3}$$

where P_j is the priority score of the jth culvert, s_{ij} is the score or rating of the jth culvert on the ith criterion and w_i is the weight or value of the ith criterion.

The MCDA score consists of the MCDA Condition score, MCDA Inventory score and MCDA Hydraulic score. The criteria are the factors which will affect the decision as to which assets should be prioritized for funding. The condition numerical scores (from 0.1 to 1) are assigned to each unique value for all factors of the asset. The decision matrix is populated by assigning weights to all attributes. The weights are assigned by expert judgment based on the importance of each attribute in relation to the decision.

9.1 Deterioration Modelling

The Culvert State obtained from the MCDA Condition Score was used to develop regression model between the overall culvert state as a dependent variable (DV) and the culvert components condition states as independent variable (IV).

Figure 7 shows the graph between Culvert State (from MCDA Condition Score) vs Predicted (from Regression) equation. The overall Culvert State regression equation was used to predict culvert overall condition in each year of the analysis.

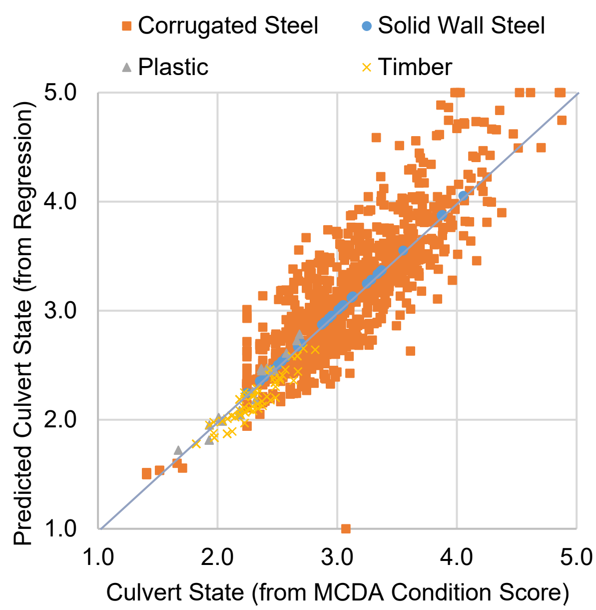

Figure 7: Inspected Culvert State (from MCDA Condition Score) vs Predicted Culvert State (from Regression)

To determine the deterioration rate of the different components, the typical lifespan of each component was determined by expert judgement. Then that lifespan was broken up into periods spent within each condition state. Deterioration tends to be more rapid at the end of the lifespan. For instance, concrete spalling leads to rust, leading to more spalling in an accelerating process. Once these periods were established, they were converted to equations to estimate condition at any age.

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Deterioration modeling for the components listed were carried out individually for all components of culverts such as embankment, channel alignment and protection, end treatment and appurtenant structures, corrugated metal barrel, seams, joints, concrete barrel, concrete footing and invert slab, plastic barrel, masonry barrel, and timber barrel.

9.2 Engineering Economic Analysis

Engineering economic analysis was carried out to identify and select the most efficient strategy alternative, including a do-nothing scenario. The condition-based treatments and climate adaptation options were evaluated through economic analyses, as it monetizes the costs and benefits associated with treatment strategies over a specific analysis period to be compared. The economic analysis for condition-based treatments and climate change adaptation options quantifies the extent of cost and benefit of options.

9.2.1 Scope of Economic Analysis

The scope of economic analysis was tailored to PSPC objectives, detail and reliability of climate projections in previous tasks and appropriate time horizon for culvert assets. The economic analysis considered direct costs and benefits of the adaptation options to the Stakeholders and travellers, broader environmental impacts as well as a reduction in risk while comparing alternate adaptation options.

This life-cycle cost analysis calculates each strategy's total cost over the analysis period (in this case, 50 years). The total cost includes direct/agency costs (the capital cost to stakeholders arising out of repairing/replacing the asset after a climate-related event, ongoing maintenance and residual value, if applicable) as well as road user costs (vehicle operation costs, delay/detour costs, environmental cost and so forth).

The total life-cycle cost for each strategy under consideration is compared to the life-cycle costs of a hypothetical “do-nothing” strategy, which is essentially the status quo maintenance regime. Any reduction in life-cycle cost, relative to the do-nothing strategy, represents the “Net Benefit” of applying a particular strategy. All costs are computed in terms of present dollar-cost terms using an appropriate discount rate.

The cost of the initial implementation of a Strategy, (called an improvement treatment(s)), is the Capital Cost of the initial improvement. Subsequent downstream costs are expressed in terms of $Risk. A cost/benefit, or net benefit, comparison between developed adaptation strategies for identified assets, was carried out.

9.2.2 Economic Metrics

The economic metrics are calculated through the life-cycle cost analyses of the adaptation strategies and ultimately used to inform strategies' comparison. Economic metrics include:

- Net Present Value (NPV) of Benefits
  - **Net Present Value Cost**: The Present Value Cost is the discounted total expenditures by the agency in terms of the annual maintenance cost, treatment (strategy) cost, end of life replacement cost and the benefits in terms of salvage value during the considered analysis period of 50 years. When comparing similar alternate strategies, the strategy with the lowest NPV Cost is considered as the most cost-effective one.
  - **Present Value $Risk:** The Present Value $Risk is the discounted total monetary risk of the asset over the asset's life-cycle due to the probability of unsatisfactory performance due to Extreme Weather event and/or Structural Failure, depending on the asset.
  - **Present Value $Benefits in Reduced Risk:** Net Present Value $Benefits is the difference between the Present Value $Benefits (reduction in $Risk over base case strategy) for each strategy and the Net Present Value Cost for each strategy over the analysis period. When comparing alternate strategies, the strategy with the highest NPV $Benefits is considered as the most cost-effective one.

- Benefit-Cost Ratio (BCR)
  - **PV $Benefits in Reduced Risk over PV Cost Ratio:** The numeric ratio expresses the PV $Benefits (in Reduced Risk) of the strategy relative to PV Cost. When comparing alternatives, the strategy with the highest PV $Benefits and PV Cost Ratio is the most cost-effective one.

The life-cycle costs for implementing each condition-based maintenance, replacement treatments, adaptation upgrade and do-nothing strategy were calculated. The costs considered in the LCCA include both "direct costs," the cost directly incurred by the PSPC, and "user costs," costs that users of the road would incur rather than the PSPC. A discount rate of 4.0% was used in this study.

The consequences for all assets were accounted for in the analysis in terms of owner and user consequences. For culverts, the failure mechanism will either be a culvert's washout due to extreme event or structural failure. The failed culvert is replaced with a new culvert as a direct consequence of asset failure.

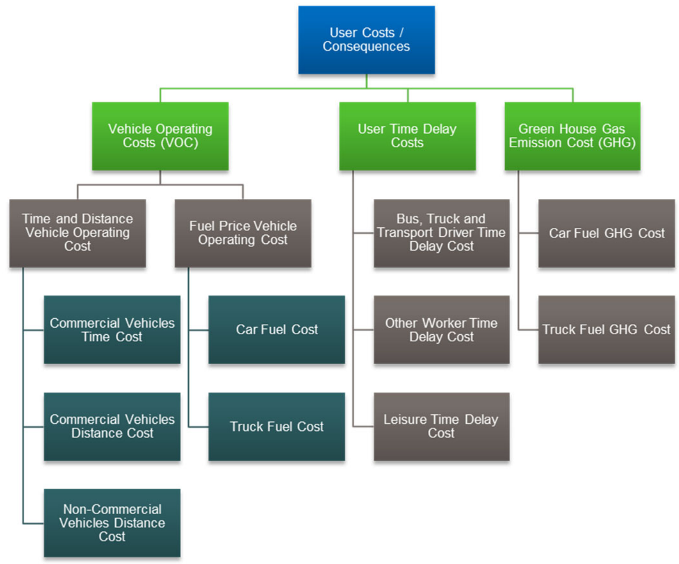


Figure 8: User Costs Considered in Assessment

The user consequence is the monetary loss to users of the road due to the traffic flow disruption because of the asset's failure or unsatisfactory performance. For drainage assets, user consequence is equal to the user costs calculated earlier. Figure 8 provides the user costs considered in the assessment.

$$User\ Consequence = User\ Cost_{VOC} + User\ Cost_{Time\ Delay} + User\ Cost_{GHG} \tag{4}$$

9.3 Estimated Benefits

The IPCC’s Fourth Assessment Report (AR4) defines benefits as “the avoided damage costs or the accrued benefits following the adoption and implementation of adaptation measures.” The benefits in infrastructure hazard mitigation and resiliency projects are typically damages and losses to owners and users due to adaptation measures.

$$BENEFITS = \sum(\$Risk\ without\ Adaptation\ Measure) - \sum(\$Risk\ after\ Adaptation\ Measure) \tag{5}$$

Avoided damages or benefits are the reduction in monetary losses as a result of an adaptation measure. The project benefits occur over a future period, while most adaptation measures costs are incurred upfront and in the present. Therefore, benefits are more difficult to estimate than costs.

In the BCA, the alternative adaptation measures were compared with either a “base case” strategy or a “do-nothing” strategy. “Do-Nothing” assumes that the asset will be left as is and will not be regularly maintained or periodically upgraded over its useful life. The “base-case” assumes that the PSPC will replace the asset after its design life with the same size asset.

Benefits in monetary risk reduction for "replacing the culvert" and benefits in monetary risk reduction to "upgrade the existing culvert" were calculated separately for drainage assets. The benefits of all adaptation upgrade strategies of the culvert assets were compared with the "base case" strategy that the culvert will be replaced at the end of effective design life to calculate upgrade benefits. The benefits of culvert replacement strategy with the same size were compared with the "Do Nothing" strategy, which assumes culvert will not be regularly maintained or replaced after its useful life to calculate replacement benefits. The adaptation options considered for drainage assets were considered incremental approaches to replace assets for a return period of 100, 200, 500, and 1000 years.

9.4 Analysis and Modelling

Tetra Tech used Deighton's Total Infrastructure Management System (dTIMS) software for data analysis and modelling. The vulnerability and risk assessment modelling methodology (St. Michel, Reggin, & Leung, 2017) and multi-strategy life cycle cost analysis were carried out in the software. The dTIMS database was populated with the asset inventory data for drainage assets required to complete the analysis.

The multi-strategy life cycle cost analysis was carried out using the trigger criteria established for culverts. Treatment trigger criteria are sets of conditions that define the range of treatments to be considered in the cost-benefit analysis. The trigger criteria are established to analyze all possible permutations of applicable adaptation treatments within the required analysis spectrum

Triggers were based on avoiding deterioration to a severe condition, how the deterioration of the component could contribute to the deterioration of other components, and how the component effected the culvert function. Replacing an existing culvert with a new one, with the same size culvert or upgrading culvert to a larger size culvert are another set of treatments considered in the analysis.

In LCCA and CBA modelling, when a treatment is applied to an asset, it resets the analysis variables. The analysis variable's resetting is done to quantify the change in asset condition due to the treatment. The asset's $Risk value is reset by resetting several input parameters, as defined in the earlier sections. After an adaptation treatment is applied to an asset, it resets several analysis parameters sequentially to a value specific to the adaptation treatment to get the $Risk.

10.0 CAPITAL WORKS PROGRAM

The cost-benefit analysis included all culverts (2101) along the Alaska Highway project limits with the exception of the Bridge-Culverts which were beyond the scope of the project. The 2101 culverts also included the culverts where needs to be upgraded due to increased flow due to climate change. The cost-benefit analyses prioritize the culvert replacements and upgrade by modelling the cost of upgrading the culverts and the expected benefits in terms of reduction in risks. This cost-benefit analysis identified the culvert upgrades and replacements which would be a beneficial investment for the Alaska Highway project in terms of reducing monetized risk of failures.

Budget investment strategies are adopted to achieve the culvert condition and system performance set in both the short term and the long term. The budget scenarios were selected to meet the following criteria:

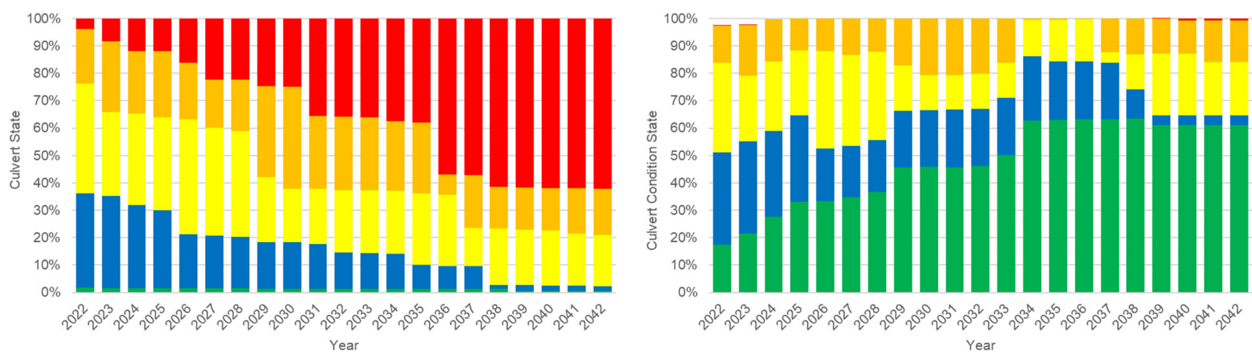
- Unconstrained funding (hypothetical scenario with unconstrained funding and resources);
- No funding available (Do-Nothing);

- Funding required to maintain the 2021 overall network asset condition; and
- Alternative funding levels to demonstrate future forecast condition depending on the level of funding that can be obtained.

In all of the funding scenarios (excluding the "Do-Nothing") the first five years (2023 – 2027) capital plan included a set of culvert replacements and upgrades selected directly from the results of the 2021 culvert inspection program on a "worst condition first" basis. These culverts were committed by year in the capital plan, and the cost of these committed capital replacements amounted to ≈$40 M over the five-year period. The following six types of 20-year funding scenarios were considered:

1. No Funding Available (Do-Nothing);
2. **Unconstrained Funding**: maximize the benefits subject to the deterioration curves and intervention criteria with an unconstrained budget;
3. **Optimal Condition Uniform Funding**: a uniform funding stream sufficient to achieve maximum network health as defined by the unconstrained analysis;
4. **Maintain Condition Uniform Funding:** funding required to maintain overall network health at current levels;
5. **Assumed Network Current Funding:** assumed current funding level based on the costs of the currently committed capital works plan; and
6. **Improved Condition Funding (Draft Capital Plan):** a uniform funding level to improve the current network condition.

Figure 9 shows the culvert condition distribution for No Funding and Unconstrained funding scenarios. The analysis of the Do-Nothing scenario shows that the overall condition of the network will continue to deteriorate over the 20-year analysis period. The unconstrained budget scenario shows that the significant improve in network condition, as in this scenario, an organization does not have any restrictions on how much money it can spend on assets.



1) No Funding Available (Do-Nothing) 2) Unconstrained Funding ($$$$$)

Figure 9: Culvert Condition Distribution for No Funding Available and Unconstrained Funding

The performance estimates of Culvert State were completed, and LCCA was carried out to determine an optimal program for the six analyzed budget levels using the defined benefits. Figure 10 shows the six budget scenarios comparison.

The figure shows a significant improvement in condition for the Unconstrained Funding scenario. It shows that the Optimal Condition Uniform Funding will be improved over twenty years to the same level as Unconstrained Funding. Budget scenarios where culvert condition continues to deteriorate are considered insufficient. A budget between Maintain Condition Uniform Funding and Optimal Condition Uniform Funding is preferred, as it will improve the network condition over twenty years.

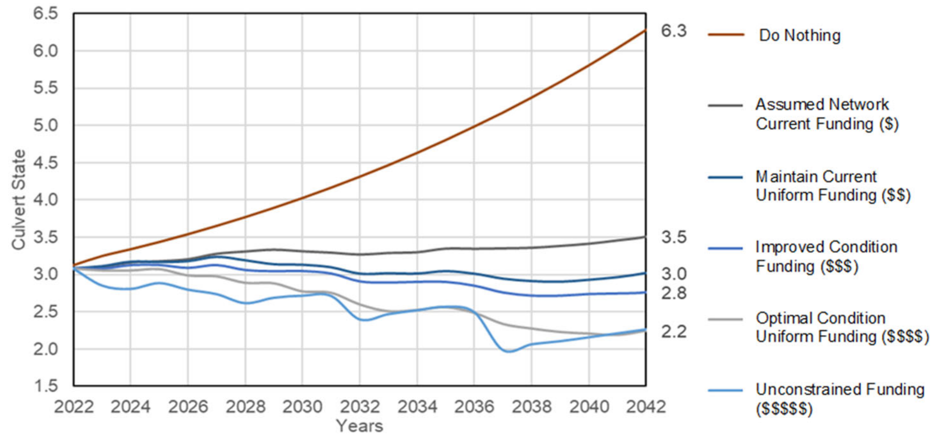
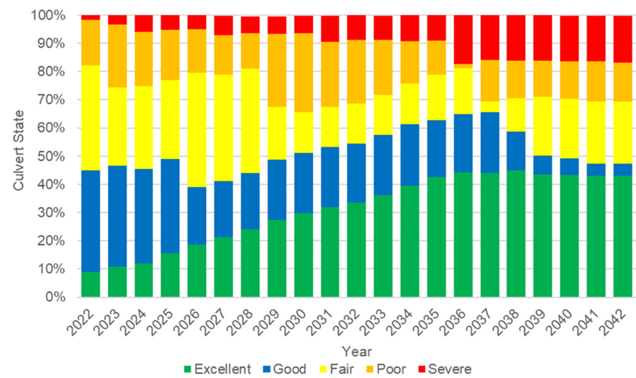


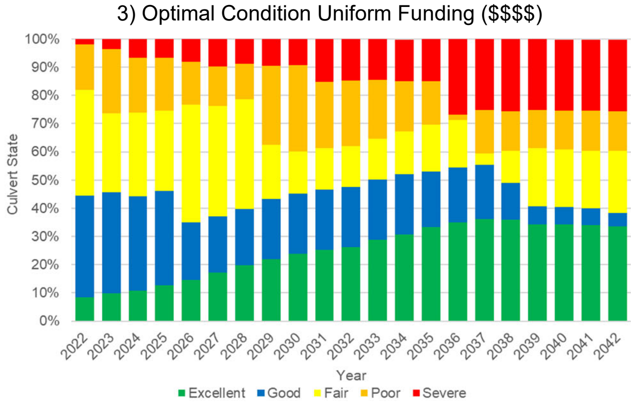
Figure 10: Budget Scenarios Comparison in terms of Culvert State

Figure 11 shows the culvert condition distribution for budget scenarios. The figure shows that while the overall condition is maintained in the Maintain Condition Uniform Funding Scenario, the number of culverts in severe and poor conditions will increase over the years.

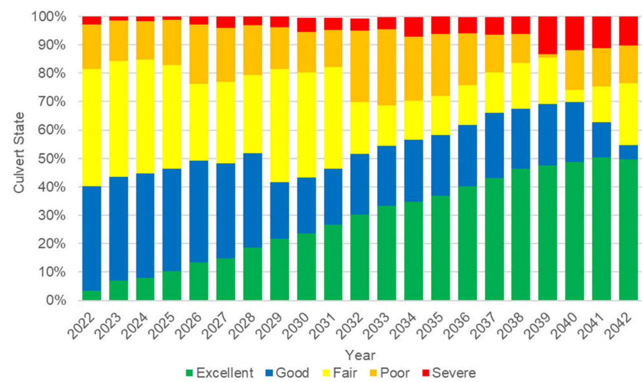
3) Optimal Condition Uniform Funding ($$$$)



4) Maintain Condition Uniform Funding ($$)



5) Assumed Network Current Funding ($)



6) Improved Condition Funding ($$$)

Figure 11: Culvert Condition Distribution for Budget Scenarios

The number of culverts in poor condition increased in 20-years for the Improved Condition Funding scenario as the program prioritize the replacement of culverts crossing the highway over culverts crossing sideroads due to higher benefits in terms of reduction in monetary risk.

11.0 CONCLUSION AND RECOMMENDATIONS

The established capital works program should be aligned with the strategic asset management plan. The integration ensures that the culvert capital works program is aligned with the long-term objectives and goals of the PSPC. The integration helps to ensure that the necessary culvert capital works are completed in the right areas assigned under the PSPC's strategic plan. The capital works program includes budgeting for capital works projects, identifying the culverts that need to be upgraded or replaced, setting timelines for the projects.

It also helps to ensure that the capital investments are properly allocated to maximize the returns on investment. The integration also helps to ensure that the capital works program is properly executed. Finally, the integration helps to ensure that the PSPC is able to identify and address any potential risks associated with the capital works program.

The framework identifies five decision-making strategies by effectively incorporating results into:

- Project Level Design and Engineering;
- Asset Management;
- Transportation Planning;
- Project Development and Environmental Review; and
- Transportation Systems Management and Operations, Maintenance, and Emergency Management.

Culvert data collection and a risk-based life-cycle economic analysis were conducted for all the culverts in the network to forecast the culvert condition for 20 years. The purpose was to forecast the overall condition of the network-based, to identify the replacement, adaptation and maintenance needs, and the associated budget to improve the culvert condition.

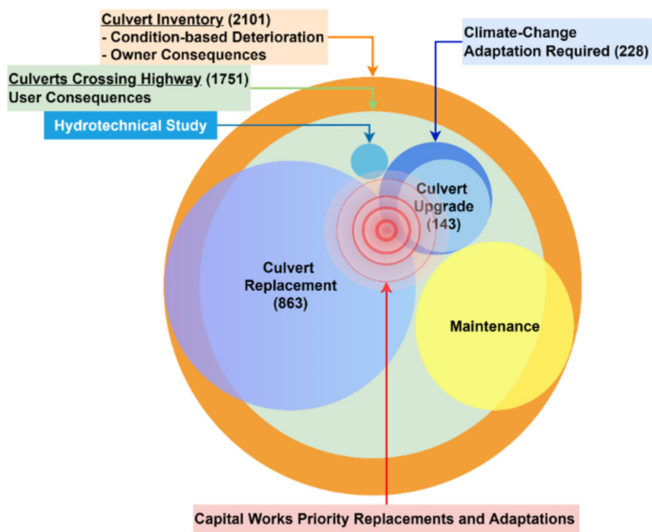


Figure 12: Capital Works Priority (20-Year)

Figure 12 shows the capital works priority for treatments in terms of replacement and adaption based on the cost-benefit analysis.

The program as presented is intended to be utilized as a tool for the long-term planning of the management of the culvert assets. Project-level engineering must be completed prior to initiating design and construction. The program should be adjusted for proximity to each other, cost feasibility, treatments homogeneity, operational logistics, and timing to develop suitable tender packages for construction.

Finally, the program should be reviewed periodically to ensure that the information is up to date and that the plans are still relevant for the current management of the culvert assets. This will help to ensure that the management of the culvert assets remains effective and efficient, and that the investments made are providing the desired outcomes.

12.0 ACKNOWLEDGMENT

We would like to extend our sincere gratitude to the PSPC team for their invaluable support and guidance throughout the course of this project. Their expertise and insights significantly contributed to the success of this project. Furthermore, we are grateful for the generous funding provided by PSPC, which enabled us to conduct this important research project and advance the field of culvert inspection and management.

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