The Economic Costs of Culvert Failures

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ABSTRACT

As America's infrastructure ages, the risk of failures increases. Bridge corrosion, road and utility degradation are becoming an increasing concern for agencies across the United States. Culvert pipe failures under major roads throughout the United States are no different as these catastrophic failures have resulted in sinkholes, road damage and flooding. These incur great costs to:

- government agencies that have to fix/replace pipes at emergency rates
- private land owners who are often effected by flooding damage, and,
- motoring public in terms of user delays.

Additionally, safety and liability issues also arise due to such failures.

Actual replacement cost and user delay costs are often not considered in Life Cycle Cost Analysis (LCCA). Therefore, a methodology for including these costs into a typical LCCA is recommended. As part of this report, all 50 United States and 7 Canadian agencies were surveyed regarding culvert failures and LCCA Issues. Of the 25 responding agencies, only three agencies applied some form of LCCA, while 15 agencies documented their failures on a cursory or memory basis. Several recent examples of failed culverts are reviewed here to demonstrate the costs and circumstances surrounding culvert failures. The study concludes that a national tracking of culvert failures would help agencies better understand the risks associated with failure. Tracking would also help in identifying trends as well as quantifying the costs associated with failures. Based on the tracked information, a risk factor could also be incorporated in future LCCA calculations.

INTRODUCTION

There have recently been a number of culvert failures in North America. Such sudden failures cause a road section to collapse, thereby creating a sinkhole. This poses a major safety risk, as well as tremendous disruption to traffic. The purpose of this paper is to:

- quantify the economic implications of culvert failures including related user delay costs;
- find out if the risk of failures is being considered as a selection criteria; and,
- identify the need to document failures.

User delay costs are attributed to highway users when delay occurs due to road closures and detours. Such costs can be significant and consideration should be given to incorporate them in Life Cycle Cost Analysis (LCCA).

Various types of pipe material have different life expectancies. As more culverts fail, a major concern is whether government agencies have a plan to monitor and replace culverts based on either inspection, or culverts reaching their expected life. Without a plan followed by action, failing culverts will have to be replaced at emergency rates instead of normal rates. By examining case studies involving emergency replacement instead of a normal replacement, an emergency replacement factor can be determined. This paper does not address the life expectancy issues in the industry, but instead identifies the user delay costs and replacement costs for an assumed life expectancy. This consequently allows a better comparison of pipe materials based on costs.

Culvert pipes can be classified into two categories, flexible and rigid. Flexible pipes include plastic and a range of metal and metal-coated pipes. Rigid pipes include reinforced concrete pipe, non-reinforced concrete pipes and clay pipe. In flexible pipes, the majority of the structural strength comes from load transfer to the surrounding soils. In contrast, structural load on the rigid pipes is bore primarily by the pipe itself with a much smaller proportion of load transferring on the surrounding soil. While the specification for the type of culvert pipe to be installed resides with the governing agency, many agencies have not distinguished a qualitative difference between the types of pipe. The installation cost varies by pipe material and many agencies select the less expensive option. However, this may be a short-term decision that does not consider the long-term costs. Therefore, LCCA should be considered to determine the overall costs.

In this study, all states in the United States and Canada were surveyed regarding their culvert practices. The surveys were used to develop an understanding of what procedure and criteria are employed by the various agencies in selecting the best suitable pipe material for their culverts. The surveys also attempted to gain an insight into the documentation practices employed by each agency to track the failures in their jurisdiction.

Failure case studies were examined to assess the true costs of the installation of a culvert pipe during emergency circumstances as opposed to normal, planned installations. In any risk analysis, the pipe material must be considered. Once future culvert failures are documented and a statistical sample can be ascertained, a risk assessment can quantify the potential hazards and a risk factor can be assigned to each pipe material. This should not preclude the use of one pipe versus another but at least help in assessing the trade-offs between initial installation cost and future reliability/risk.

LITERATURE REVIEW

In typical LCCA, certain assumptions are made about the life of a pipe material. This is a contentious topic because an exact design life for each pipe material has not been defined. Certain agencies such as the US Army Corps of Engineers, and American Association of State Highway and Transportation Officials (AASHTO) and ASTM have made recommendations to help states and cities select culvert pipes, but each agency also assumes their own life expectancy based on experience or literature.

The Missouri Department of Transportation [*1,2*] conducted a field evaluation of 3,897 culvert pipes including 1,642 reinforced concrete pipe (RCP) and 2,255 corrugated metal pipe (CMP) culverts. This study that stratified culverts by age identifying that 45.6% of the CMP pipes needed replacement whereas 0.3% of the RCP required attention. Some of the CMP deterioration could be attributed to a change in the pipe gauge. According to a Kansas Department of Transportation study [*3*], more rapid deterioration of CMP has been quantified since the late 1975s when standards changed to allow a lighter gauge metal in pipe construction. While the lighter gauge pipes may have had adequate structural support from surrounding soils, the change in standard was reported to lessen pipe design life by nearly 20 years because of less metal to corrode at the same corrosion rate.

As these pipes reach the end of their useful life, agencies should replace them. If not, these pipes are destined to fail and create a traffic danger and congestion point. The number of agencies that are actually inspecting and tracking age/condition of culverts and performing maintenance/ replacement as needed should be explored.

The United States Army Corps of Engineers [*4*] identified recommendations on pipe design life by material in a March 1998 report. The following are quotes from that report:

- Service Life: "For major infrastructure projects, designers should use a minimum project service life of 100 years when considering life cycle design."
- Concrete: "Most studies estimated product service life for concrete pipe to be between 70 and 100 years. Of nine state highway departments, three listed the life as100 years, five states stated between 70 and 100 years, and one state gave 50 years."
- Steel: "Corrugated steel pipe usually fails due to corrosion of the invert or the exterior of the pipe. Properly applied coatings can extend the product life to at least 50 years for most environments."
- Aluminum: "Aluminum pipe is usually affected more by soil-side corrosion than by corrosion of the invert. Long-term performance is difficult to predict because of a relatively short history of use, but the designer should not expect a product service life of greater than 50 years."
- Plastic: "Many different materials fall under the general category of plastic. Each of these materials may have some unique applications where it is suitable or unsuitable. Performance history of plastic pipe is limited. A designer should not expect a product service life of greater than 50 years."

However, the survey discussed later in this paper shows a wide range of assumed life expectancy by pipe material used by these agencies.

AASHTO, in its 1991 Model Drainage Manual [*5*] also documents the recommended practice for culverts selection and design. While general hydraulic design criteria is recommended, the AASHTO Drainage Manual also gives recommendations about the costs/risk analysis aspect of pipe material selection. This includes:

- Material selection shall include consideration of service life that includes abrasion and corrosion.

- Culverts shall be located and designed to present a minimum hazard to traffic and people.
- The detail of documentation for each culvert site shall be commensurate with the risk and importance of the structure. Design data and calculations shall be assembled in an orderly fashion and retained for future reference as provided for in the Documentation Chapter.
- Culverts shall be regularly inspected and maintained.
- The material selection shall consider replacement cost and difficulty of construction as well as traffic delay.
- The selection shall not be made using first cost as the only criteria.
- Select an alternative which best integrates engineering, economic and political considerations.
- The chosen culvert shall meet the selected structural and hydraulic criteria and shall be based on:
    - construction and maintenance costs
    - risk of failure or property damage
    - traffic safety
    - environmental or aesthetic considerations
    - political or nuisance considerations
    - land use requirements

The AASHTO Drainage Manual documentation supports the need to consider all aspects of costs, including traffic user delays and risk of failure. Field results are the primary measure in a risk assessment as it includes the pipe performance regardless of pipe material or installation abnormalities. If the installation procedures are improper this produces an inherent risk that can be accounted for by historic performance records. As construction inspection funding by government agencies is scarce, reliance on contractor's quality control procedures greatly impacts installation quality. Therefore, there is an inherent need to track failures and document pipe performance on a national level to identify the performance by pipe material.

A typical consideration in cost analysis for culvert selection is material cost. Other costs include excavation, backfill, compaction, labor, traffic control, and road repair. When only pipe material costs are considered for an initial installation, the future implications for replacing the pipe are often neglected.

PROPOSED LIFE CYCLE COST ANALYSIS

This section describes a method developed to compute the total cost (T) of installing a culvert over a given time horizon (H), usually 100 years. The method is modified from an established Engineering Economics life cycle methodology [*6*]. The total cost (T) in Equation 1 is the sum of the culvert's installation costs ($I_{H(L)}$) for all installation within the horizon year, and the cost of associated user delay (D).

Total Cost (T) = Installation/Replacement Cost ($I_{H(L)}$) + User Delay (D)…………Equation 1

Installation/Replacement Cost

An explanation for installation/replacement costs is given below and shown in equation 1a. The installation/replacement cost (I_H) is computed from the initial installation cost (I_I) based on the present value, and then projected at a discount rate (r) for any replacements during the time horizon H depending on the assumed life of the culvert (L). Note that the discount rate is the differential between inflation and interest rates. Therefore,

$$I_{H(L)} = {}_{k=0}\Sigma^{n} I_I (1+r)^{kL} \text{ where, } n = (H/L)-1 \text{ ……………………………………Equation 1a}$$

For example, the cost of installation for a 100-year horizon for pipes having different life cycles is shown in Table 1. This cost is for pipes of assumed lives of 25, 50, and 100 years, based on a 4% discount rate [7]. Further, it is assumed that initial installation cost for each pipe is approximately the same.

→ Table 1 here.

User Delay Costs
The cost of delay (D) experienced by the user during the culvert's installation is computed based on:

- the roadway Annual Average Daily Traffic (AADT) which the culvert is being installed;
- the average increase in delay or congestion the installation is causing to each vehicle per day ('t' in hours);
- the number of days the project will take (d);
- the average rate of person-delay in dollars per hour (c_v);
- the average rate of freight-delay in dollars per hour (c_f);
- the percentage of passenger vehicles traffic (v_v);
- the vehicle occupancy factor (v_{of}); and
- the percentage of truck traffic (v_f)

Note the k factor allows each user delay cost to be tied to the specific time period of the failure year where the variables may change in the future.

$$D = {}_{k=0}\Sigma^{n} [AADT_k * t_k * d_k *(c_{vk} * v_{vk} * v_{ofk} + c_{fk} * v_{fk})] \text{ ……..…………Equation 1b}$$

For example, the User Delay per day for different AADT levels and delay is shown Table 2 with the following equation variables:

Average Established Delay costs in Dollars [8]:
c_v = $17.18 per person-hour of delay
c_f = $50 per freight-hour of delay
Typical Traffic Assumptions [9]:
v_v = 97% vehicle passenger traffic
v_f = 3% truck traffic
vehicle occupancy factor = 1.2 persons per vehicle

→ Table 2 here.

SURVEYS

A 'General Survey' questionnaire was sent out via e-mail to all 50 US states and 7 provinces in Canada. This survey requested information on whether a LCCA or risk assessment is performed for culvert material selection and if they utilized the pipe selection criteria recommended in the 1991 AASHTO Model Drainage Manual [*5*]. They were also asked if they considered emergency replacements costs and user delay costs. Agencies were further asked if they used any other criteria to select pipe material prior to installation. The survey queried for documentation on any failures during the past 10 years, and their current procedure of documenting culvert failures.

If any of the agencies documented failures in their jurisdiction in the past 10 years, a more specific survey was conducted with the agency. This second survey was centered on obtaining failure specific information such as: location, duration of repair, culvert details and the costs involved in repairing or replacing the culvert. Samples of General and Specific Survey forms used in this study are shown in Figure 1 and Figure 2.

→ Figure 1 here

→ Figure 2 here

Survey Results

Of the 57 agencies queried, 25 agencies responded to the survey. The following are the observations made from the survey results:

- Only four of the 25 agencies that responded to the survey stated that the agency performs a least cost analysis for pipe material selection.
- Different agencies assumed different life cycles for each material. Assumed life of Reinforced Concrete Pipes (RCP) and Non-Reinforced Concrete Pipes (NRCP) varied from 50 to 100+ years, assumed life of Corrugated Metal Pipes (CMP) varied from 35 to 50 years, assumed life of High-Density Polyethylene (HDPE) pipes varied from 30 to 100 years, and assumed life of Poly Vinyl Chloride (PVC) pipes was 50 years. None of the respondents used Vitrified Clay Pipe (VCPs) and therefore no data was available regarding those pipes. The frequency distribution of the assumed life expectancy from the survey for various pipe materials is shown in Table 3.

→ Table 3 here.

- Five of the 25 agencies provided data regarding cost of pipes. Results indicated that cost varied from agency to agency and also varied by material and size of the pipe. Some agencies also mentioned that the cost of the pipe was negligible as compared to the cost of earthwork, traffic control and installation/labor costs.
- Only two of the responding agencies consider the risk of failure while performing a cost analysis as recommended by the 1991 AASHTO Model Drainage Manual.

- Only five agencies considered emergency replacement costs. Seven agencies considered user costs that could be incurred in the event of a culvert failure. This is confusing as only four states responded that they perform a LCCA.
- Fifteen of the 25 responding agencies document culvert failures occurring within their jurisdiction. However, the level of detail in documenting these failures greatly varied from agency to agency. Most written documentation of the specific culvert failure was unavailable.
- Some agencies did not allow the use of a certain pipe type above a particular AADT level. From the responses, 42% of the agencies stated that AADT was a consideration in pipe material selection, often only allowing rigid pipe on high AADT roads. This identifies that risk and traffic delay is indirectly considered in pipe selection, often without conducting LCCA.

It is important to note that the survey reflect opinions and not factual information. This is evident from the wide range of perceived pipe design life for a given pipe material. The survey is however important because it identifies the common perceptions of the various agencies and the process they are using in the pipe selection. It further identifies that while few agencies use LCCA based on the AASHTO recommendations, there are natural tendencies by almost half of the surveyed agencies to require certain pipe types on higher AADT roads. This identifies the perceived inherent benefits of reducing risks and utilizing longer life pipe materials on critical roadways.

CASE STUDIES

- I-70, East of Vail, Colorado

  A culvert failed on I-70 on 6/01/03. The road carries an Average Daily Traffic (ADT) of 20,950 vehicles with 12% heavy vehicles. Four lanes, two in each direction, were damaged requiring a 54-mile long, 2-hour detour through Leadville on a twisty 2-lane road. Two lanes were temporarily re-opened after 4 days with the speed limit lowered from 55 mph to 35 mph. The final repair was completed after 49 days on 7/20/03. The failure occurred during a large storm when a 66” diameter CMP culvert, 85’ to 100’ long, failed due to rusting. The estimated age of the pipe is between 35-60 years. The destroyed pipe was replaced with another circular corrugated metal pipe of the same diameter. The culvert failure also caused damage to city streets and 28 homes including 2 homes that suffered structural damages. The total cost of the culvert failure was $4.2 million.

- I-480 Milepost 22.16, near Maple Heights, Ohio

  A culvert failure occurred on I-480 on 12/14/01. The road is estimated to have an ADT of 167,600 vehicles and 8% heavy vehicles. One lane was damaged but traffic along the route was maintained with lane closures over a certain stretch. The final repair was completed after 8 days on 12/22/01. The failure occurred when a 60” diameter CMP failed. The estimated age of the pipe was 50-60 years. The destroyed pipe was replaced with reinforced concrete pipe of the same diameter. The replacement cost of the culvert was $384,000. The original pipe was most likely installed by a private developer during the construction of a residential neighborhood south of the interstate. As the interstate was widened, this existing conduit was extended by ODOT. Additionally, fill was added above the culvert subjecting the pipe to greater loads. A separation of the pipe joints likely caused infiltration of the backfill material, and thus a loss of support for the pipe.

- SR-79 at Milepost 1.63, near Village of Buckeye Lake, Ohio

A culvert failure occurred on State Route-79 on 6/24/03. The road is estimated to have an ADT of approximately 5,000 vehicles with 30% heavy vehicles. Two lanes were damaged and a 3-mile detour route was used to divert the traffic. Vehicles took approximately 15 minutes and trucks took approximately 20 minutes to travel the detour. Final repair was completed after six days on 6/30/03. The failure occurred when a 30" diameter CMP failed due to heavy rust resulting is a 50' long culvert section loss. The estimated age of the pipe was 25-30 years.

- SR 173, West Jordan, Utah

A culvert failed on SR 173 on 6/16/03. The road carries 38,675 ADT with 3% heavy vehicles. Two eastbound lanes were damaged and a 1.05 mile detour route was used to divert the traffic. It took vehicles an additional 30 minutes in the peak times and 10 minutes in the off-peak times to travel the detour. The failure occurred when an elliptical, 72" equivalent diameter CMP collapsed due to rusting. The age of the pipe was estimated at 20 years. Final repair was completed after 5 days with another CMP of the same size. Crews desired to install a concrete pipe, but CMP was used due to the quick availability.

- I-70 Eisenhower Tunnel, 60 Miles West of Denver, Colorado

A culvert failed outside of the I-70 Eisenhower Tunnel on 6/12/03. The road is estimated to have an ADT of 20,950 vehicles with 12% heavy vehicles. Two westbound lanes were damaged and trucks over 26,000 lbs had to travel via a 30-minute long detour. The detour passed through Loveland Pass and over the continental divide at 11,000 feet. The final repair was completed after 7 days. The failure occurred when a 60" diameter CMP failed due to corrosion of the culvert pipe. The estimated age of the pipe is 30 years. The damaged pipe was shot-creted at a cost of $45,000.

- I-75 at milepost 227 near Prudenville, Michigan

A culvert failed on I-75 on 4/22/03. The road is estimated to have an ADT of 5,100 vehicles with 13% heavy vehicles. Two lanes were damaged and a 16.5-mile long detour had to be provided. The detour took vehicles and trucks an extra 20 minutes to travel. The final repair was completed after 6 days. The failure occurred when an elliptical 73"x55" CMP arch, failed due to extensive corrosion of a 50' section of the culvert pipe. The estimated age of the pipe is 30 years. The destroyed pipe was replaced with a 72" corrugated metal pipe at a cost of $95,000.

- Highway 401 at Milepost 325 km, near Milton, Ontario Canada

The culvert failure occurred on 8/9/00. The road is estimated to have an ADT of 300,000 and 20-25% heavy vehicles. Two lanes were damaged and an 8.4-mile long detour, had to be provided. The detour took vehicles and trucks an extra 4 hours to travel. The final repair was completed the next day. The failure occurred in a corrugated metal pipe of 30" diameter, approximately 25 years old.

Table 4 identifies the costs of the above failures related to emergency costs and how a longer life pipe used during initial installation would have saved long-term costs and also identifies the associated cost-benefit ratio.

→ Table 4 here.

All the culvert failure cases obtained from the survey were related to failures in corrugated metal pipes, mainly occurring due to aging. Some of the failures had met the agencies expected life for that pipe type but no planned replacement was scheduled. This raises the concern that there is a lack of inspection and/or tracking of useful life expectancy. Some agencies replaced their culvert failures with longer life pipe materials whereas other agencies replaced the failed pipes with pipes of the same material. It would be interesting to investigate in these cases if this was due to quick availability and/or lower initial installation costs, or a LCCA.

Several agencies were observed to have varying practices with respect to culvert failures. Most agencies had a reactive approach, while few had a preventive approach. Most agencies responded to culvert failures once they were noticeable and required immediate attention. One agency inspected all culverts within its jurisdiction every 2 years and there are no reported failures from that agency. Another agency oversized their culverts and when they aged, they were lined with another culvert pipe of smaller diameter, thereby minimizing the costs involved in a failed culvert.

Apart from the culvert failures on highways that are listed above, failures are also commonly observed in areas such as parking lots. As such failures occur in off-road areas, these are typically less impacting to user delays as there is no ADT associated with them. Though such failures have costs of lost business associated with them, repairs are done on a non-emergency basis and therefore usually at lower emergency costs. Culvert failures in parking lots in West Bountiful, Utah and Timonium, Texas are examples of such failures that resulted in law-suits and restricted land use activity until repairs could be made.

If agencies replaced pipes regularly once the design life was met, then most culvert failures could be prevented. But the reality is that pipes are not being replaced as they approach their expected design life. Therefore, the result is emergency failures and the costs associated with the failure. It should be no surprise that the economic impacts of failures show that failures should be avoided. This may best accomplished by initially constructing culverts with pipe materials with longer life expectancies and/or by providing an established inspection, maintenance, and replacement program.

RESEARCH DIRECTION

Table 4 shows that user costs are a huge component of the total cost. Often the user delay costs are not considered in the LCCA because user costs are experienced by traffic users and is not a direct expense to any agencies budget. However, these are in fact real costs and need to be considered in the analysis. Recent studies have shown that user delays are the primary benefit in construction methods such as design-build approaches to projects and are used to justify the benefits of signal timing, ATMS systems and a range of congestion reduction measures.

By developing a national database where a “culvert failure report” can be compiled, data can be made available to other agencies and experiences across the nation can be shared. This information transfer allows for a more informed decision-making and the wide range of assumed life cycle can be better defined based on empirical data. Culvert tracking data could lead to development of a risk factor and emergency replacement factor. Both of these could be included in the cost analysis methodology, along with the installation/replacement and user costs. The new relationship would likely include a risk factor cost as included in many risk assessment methodologies. Equation 1 would then include a new factor as shown in Equation 2.

Total Cost $(T)_t$ = Installation/Replacement Cost $(I_{H(L)})_t$ + User Delay $(D)_t$ + RF_t*(ERF* I_t + $EUD)_t$……………………………………………………………………………………Equation 2

Where:
T = total life cycle cost for the given pipe type t
$I_{H(L)t}$ = installation costs and replacement costs for an H horizon year with L expected pipe life for pipe type t.
D_t = user delay during construction and replacements during the horizon analysis period (usually 100 years)
RF = risk factor for pipe type t (some probability of failure)
ERF = emergency replacement factor for pipe type t = $\dfrac{\text{Cost of emergency replacement}}{\text{normal replacement costs}}$

EUD = emergency user delay = Cost of user delay during emergency replacement

CONCLUSIONS AND RECOMMENDATIONS

As stated in the introduction, the purpose of this paper is to:

- quantify the economic implications of culvert failures including related user delay costs;
- find out how the risk of failures is being considered in selection criteria; and,
- identify methods to document failures.

It is important to bring to the forefront the issues that are currently being overlooked in a culvert pipe LCCA. This includes adding the user traffic delay costs to the LCCA. These user delay costs most often far exceed the actual construction costs. Therefore, any initial savings that occurs by installing a pipe with a lower life expectancy is quickly exceeded by subsequent replacement installations and user delays. By quantifying the additional costs of emergency replacement it is clear that an inspection/maintenance program provides an attractive cost benefit. It also shows that pipe materials with a longer life are more cost effective than materials with lower life expectancy, even if initial installation is more expensive.

These conclusions are based on the concept that a certain percentage of culvert pipes will go to failure. Our infrastructure is aging more rapidly than it can be maintained and replaced. An example is the interstate system now approaching 45 years old. Many culverts on this system utilized 30 to 50-year design life pipe and there is no immediate prospect to replace the thousands of culverts that are at, or have exceeded, their design life. At this point, it is important to consider whether a pipe with longer life is more cost-effective simply based on the likelihood that the pipe may not be replaced at the end of its design life.

Based on the results of the surveys, it was observed that there is a wide variation in the procedure and extent to which different agencies document culvert failures in their jurisdiction. While some agencies have very detailed information regarding failures and the costs related to those failures, other agencies had documented only a few of the failures.

Documenting culvert failures helps identify common failure trends based on pipe material and site conditions. Such documentation helps agencies select the most suitable culvert pipe material that is cost-effective and efficient in the long run. Consequently, there is a need to establish a standard procedure of documenting culvert failures and expand the existing limited data into a nationwide database. It is recommended that AASHTO or TRB establish a committee to develop a standardized electronic reporting format to document such failures and encourage agencies to generate a "Culvert Failure Report". If such a procedure is not in place, the information, which otherwise can provide valuable information on pipe performance, causes of failures, and economic impacts, is quickly lost after a replacement occurs. The recommended future direction involves answering the following questions and taking appropriate action:

Questions:
1. Why are many states not using the AASHTO method for LCCA for pipe selection?
2. How are agencies selecting pipe type?
3. Are initial costs the only driving factor in pipe selection without considering user delays?
4. How are agencies maintaining and inspecting pipes?
5. As many of the US culverts reach their expected life, is there a plan to replace them?

Actions:
1. Develop a national database that can be supported by TRB or AASHTO committees where culvert failures are documented using a "culvert accident report" form. The survey forms similar to those used in this study could be employed for this purpose. This information would then be made available to agencies for better understanding of:
    a. Pipe life from empirical results
    b. Failure rates and causes
    c. Impacts and emergency replacement costs relative to scheduled replacements
2. User costs need to be considered in the LCCA to provide a more representative cost analysis as these are currently being overlooked.
3. As more data becomes available, the emergency replacement cost and risk of failure should be considered as part of the LCCA.

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TABLE 1: Cost (in dollars) of Culvert Installation over a 100 Year Horizon

Horizon (H)		100 years		
Assumed life of culvert (L)		25 years	50 years	100 years
# of Replacements in 100 years (n=(H/L)-1)		3	1	0
Costs ($)	Initial Installation I_I	$I_{H\ (25)}$	$I_{H\ (50)}$	$I_{H\ (100)}$
	5,000	148,589	40,533	5,000
	10,000	297,178	81,087	10,000
	25,000	742,944	202,667	25,000
	50,000	1,485,889	405,334	50,000
	75,000	2,228,833	608,001	75,000
	100,000	2,971,777	810,668	100,000

TABLE 2: User Delay Per Day for a range of AADTs

AADT Level	Increased Delay Level				
	10 min	20 min	30 min	1-hour	2-hour
5,000	$ 17,915	$ 35,829	$ 53,744	$ 107,488	$ 214,975
10,000	$ 35,829	$ 71,658	$ 107,488	$ 214,975	$ 429,950
20,000	$ 71,658	$ 143,317	$ 214,975	$ 429,950	$ 859,901
30,000	$ 107,488	$ 214,975	$ 322,463	$ 644,926	$ 1,289,851
50,000	$ 179,146	$ 358,292	$ 537,438	$ 1,074,876	$ 2,149,752
75,000	$ 268,719	$ 537,438	$ 806,157	$ 1,612,314	$ 3,224,628
100,000	$ 358,292	$ 716,584	$ 1,074,876	$ 2,149,752	$ 4,299,504

* Rates from (reference)

TABLE 3: Assumed Pipe Life Frequency Distribution from Survey

Pipe Type / Assumed Life	RCP	NRCP	CMP	HDPE	PVC
< 40 yrs			1		
40 –50 yrs			3		
50-60 yrs	2	4	5	3	3
60-70 yrs	2				
70-80 yrs	8	2	4	3	1
80-90 yrs	1			1	1
90 -100yrs					
>= 100 yrs	4	2		2	1
Total	17	8	13	9	6

TABLE 4: Summary of Failure Case Study Information

Location	I-70-CO	I-480-OH	SR 79-OH	5400 S-UT	I-70 -CO Eisenhower	Prudenville -MI	Milton-ON
Pipe Size / Type	66" CMP	60" CMP	30" CMP	72" CMP	60" CMP	73"x55" ellipse, CMP	30" CMP
Costs of Replacement ($)	4,200,000	384,000	NA	48,000	45,000	95,000	
Length (ft)	85-100'		50'	50'	40'	50'	40'
Days	49	8	6	5	7	6	1
Impacted AADT	20950	16760	4920	19338	1257	5100	45000
Delay	120 min	60 min	20 min.	20 min.	30 min	20 min	240 min
User Cost ($)	4,046,000	3,079,000	290,000	693,000	220,000	249,000	5,033,000
Total Costs ($)	8,246,000	3,463,000		741,000	265,000	344,000	
Age (yrs)	35-60	60	30+	20	30	30	25
% Construction	51	11		6	17	28	
% User cost	49	89		94	83	72	
Normal Replacement cost	$18,000-50yr $30,000 -100 yr	$15,000 -50 yr $28,000-100yr	NA	$7,200 -20 yr$13,400-100 yr	NA	NA	NA
Total Emergency Replacement Cost	4,200,000	384,000	NA	47,800	45,000	95,000	NA
ERF	140	14	NA	4	NA		
Number of Replacements	1	1	3	4	2	2	3
Emergency Replacement Installation Costs(2003 $)	4,200,000	384,000	NA	192,000	90,000	190,000	NA
User Delay Costs for all Replacements(2003 $)	4,046,000	3,079,000	870,000	2,772,000	440,000	498,000	15,099,000
Total Costs for 100 yr Horizon (2003 $)	8,046,000	3,463,000	NA	2,964,000	530,000	688,000	NA
Estimated Cost to change to 100 year pipe (2003 $)	12,000	13,000	NA	6,200	4,500	6,200	NA
Benefit/ Cost Ratio	671	266	NA	478	118	111	NA

All cost rounded to nearest $1,000

Do you incorporate a least cost analysis in culvert pipe design?
___Yes ____No

If so, what do you use for your interest rate and inflation costs?
I = Inflation rate _______%
i = interest rate _______%

Assumed Life Cycle by pipe material (in years)
________ RCP _______NRCP________CMP________ HDPE________PVC ________VCP

Estimated Cost of Installation per linear foot
________ RCP _______NRCP________CMP________ HDPE________PVC ________VCP

In the cost analysis, do you consider the risk of failure as recommended by the 1991 AASHTO Model Drainage Manual? _____Yes ___No

Are the increased costs of emergency replacement during culvert failure considered?
_____Yes ___No

Are user costs related to detour / delays from culvert failure considered? _____Yes ___No
System Questions:

Any documented culvert failures in last 10 years? __________

Do you use any other threshold criteria for requiring one pipe material over another during initial installation?

_AADT
_Initial Installation Cost
_Assumed Life of Pipe
_Deflection Testing
_Other:__________________________________

FIGURE 1: Sample General Survey Form:

Contact - Name:__________________ Entity:__________________________
Address:_________________________________City: _____________State:____ Zip:_________
Phone: ____________________ Fax:___________________ E-mail:_______________________

Location of Culvert Failure - Road**:**___________ Milepost**:**____________
Nearest City: __________________________________ State: ________ Please attach map
Date of Culvert Failure: ________________ Number of lanes damaged:________________
Date of initial re-opening: ____________ Number of lanes temporarily opened:__________
Date of final repair: ____________________ Length of Detour:______________________
Average Daily Traffic (ADT) on highway impacted by culvert failure:__________________
Percentage heavy vehicles on highway impacted by culvert failure:_____________________
Average time to travel detour (while culvert was down and traffic was congested):__________
Average Truck time to travel detour (if different than for normal traffic): ________________
Detour Route (Describe and attach a map if possible): _______________________________
Describe the Likely cause of Failure: ____

Pipe Details
Type of Pipe: ▢ RCP ▢ NRCP ▢ CMP ▢ HDPE ▢ PVC ▢VCP
Shape of Pipe: ▢ Circular ▢ Elliptical Size of Pipe:________________________
Age of Pipe (note if estimated):____
Type and size of replacement pipe:_____________________________________

Failure Costs
Initial Cost of Culvert Installation:______________________
Cost to Repair and Replace Culvert (please note reasons for any unforeseen costs):____________
Cost of New Culvert:________________________
Cost of Traffic Control:______________________
Cost of Salaries (including overtime of government oversight and construction):______________
Cost of repairing road:_______________________
Cost of damage due to flooding related to collapse:______________________
Number of Accidents caused by failure: Property Damage: ________ Injury: ______Fatality:______
Other Indirect Costs (business loss, etc,):_______________________________
Total Cost:__________________________

Did the government entity have a budget item that dealt with replacement of existing facilities?
Please describe any other issues that may be of interest specific to this culvert failure:

FIGURE 2: Sample Specific Failure Survey Form