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In-service evaluation of culvert extensions

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In-service evaluation of culvert extensions

by

Hitesh Chawla

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Program of Study Committee:
Christopher M. Day, Co-major Professor
Peter T. Savolainen, Co-major Professor
Bora Cetin

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2019

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NOMENCLATURE

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
B/C or BCR	Benefit Cost Ratio
CMP	Corrugated Metal Pipe
DOT	Department of Transportation
EFCCR	Equivalent Fatal Crash Cost Ratio
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
GIMS	Geographical Information Management System
GIS	Geographic Information System
HDPE	High Density Polyethylene
HMCV	Hundred Million Crossing Vehicles
IRB	Institutional Review Board
LON	Length of Need
MASH	Manual for Assessing Safety Hardware
MGS	Midwest Guardrail System
mph	Miles per hour
NBIS	National Bridge Inspection Standards
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System

NHTSA	National Highway Traffic Safety Administration
PDO	Property Damage Only
PVC	Polyvinyl Chloride
RCB	Reinforced Concrete Box
RDG	Roadside Design Guide
ROR	Run-off-road
RSAP	Roadside Safety Analysis Program
SI	Severity Index
TL	Test Level
USD	United States Dollar
VSL	Value of Statistical Life

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ABSTRACT

Approximately 18% of fatal run-off-road crashes in the US are associated with either a culvert or a ditch. To reduce the risk of such crashes, safety treatments that can be implemented include installation of safety grates or guardrails, or extending the culvert outside the clear zone, as mentioned in AASHTO’s Roadside Design Guide. The existing design practices do not indicate when a particular safety treatment should be chosen over others based on the given roadway and traffic conditions. The existing literature has also been quite limited with respect to this problem. To that end, this study aims to determine the potential impacts of installing various culvert safety treatments and the cost-effectiveness of these treatments.

Crash data were analyzed for culvert related crashes from January 2007 to August 2017 using two different methodologies. The crash data, culvert data, and roadway data were then linked to each other. After removing the culverts with missing lengths and culvert sizes from the data, the final dataset included 500 crashes on 481 culverts. The crash rates were calculated for different roadway classification and highway types. Roadway scenarios were modeled in an encroachment-based simulation software called Roadside Safety Analysis Program (RSAP). Based on the estimated annual crashes from RSAP, the estimated number of crashes and crash rates for the analysis period were calculated and compared with the actual number of crashes and crash rates for each scenario. The crash rates estimated using RSAP were generally 2 to 13 times higher than the actual crash rates.

The results indicate that in most cases, installing safety grates on culvert openings is a more cost-effective solution than other safety treatments. Guardrail installation proved

to be the least effective alternative, as it appeared to increase the number of crashes as well as crash costs. Extending the culvert outside the clear zone appeared to be cost-effective to some extent, but was not found to be a better choice than installing safety grates.

CHAPTER 1. INTRODUCTION

1.1 Background

In the United States, nearly 40,000 fatal crashes occur every year (NHTSA, 2018). Around one-third of these fatalities involve a vehicle striking a roadside object, such as a culvert, tree, or utility pole. Around 18 percent of the total fatal run-off-the-road (ROR) crashes have either a culvert or roadside ditch indicated as the first harmful event on the crash report form. Table 1.1 shows the run-off-road fatalities by first harmful event for years 2012-2016 based on Fatality Analysis Reporting System (FARS) data from National Highway Traffic Safety Administration (NHTSA)(NHTSA, 2018).

Table 1.1 Run-off-road fatalities by first harmful event

First harmful event	**2016**	**2015**	**2014**	**2013**	**2012**
Boulder	33	28	29	23	27
Bridge/Pier	53	31	44	43	51
Guardrail face	315	271	283	305	291
Concrete Barrier	76	55	49	48	49
Utility/Light Pole	284	286	283	303	339
Post, Pole or other support	101	126	98	116	127
Culvert	252	240	197	215	246
Curb	404	418	398	389	357
Ditch	373	376	369	388	428
Embankment	371	316	324	395	452
Fence	153	140	128	148	150
Wall	38	30	44	49	42
Tree	913	878	823	893	1,004
Other Fixed Object	100	103	76	114	119
Total	**3,466**	**3,298**	**3,145**	**3,429**	**3,682**

Culverts are placed on the roadside to allow water to flow under a road or railroad from one side to the other side. Since these are placed close to the travel lanes, they increase the likelihood for a crash to occur. A culvert with open ends can create a hazard that can result in property damage or even serious and fatal injuries. According to the American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide (RDG), cross drainage structures or transverse culverts may create a hazard to motorists who run off the roadway (AASHTO, 2011). Some safety treatments have been suggested to reduce hazards from these structures such as:

- Redesigning using a traversable design
- Extending the structure outside the clear zone
- Shielding the cross drainage structure

Shielding a transverse culvert can be done using either guardrails or safety grates on the face of the culvert. However, for parallel culverts, safety measures as specified in RDG (AASHTO, 2011) are:

- Eliminating the structure
- Redesigning using a traversable design
- Relocating the structure to a safer location
- Shielding the structure
- Delineating the structure if nothing else works

The most common alternatives used are either extending the culvert up to the clear zone, shielding it using a guardrail, or shielding it using longitudinal grates. The choice of alternatives depends on the type of roadway, cross-sectional characteristics, and traffic conditions. Many variables need to be considered for the safety treatment of any culvert design. Among these variables are the traffic volume, culvert type, culvert size, culvert offset distance, and available safety treatment designs.

In order to provide a traversable slope, it is suggested to extend or shorten a cross drainage culvert to match the inlet and outlet slope of the culvert to the fore slope of the embankment. For culverts that cannot be made traversable, it is advisable to extend the culvert just outside the clear zone. This approach will help in reducing the likelihood of hitting the culvert. However, it will not eliminate it completely. Extending the culvert is preferable if the roadway has many other fixed objects at the edge of the clear zone.

For large culverts, it may be costly to extend the culvert beyond the clear zone. Therefore, the most effective strategy is to shield the existing culvert using longitudinal grates. This method reduces the clear opening width of the culvert, which in turn increases the safety of both the structure as well as the motorist. Full-scale crash tests have been successful in highlighting the importance of using safety grates on large culverts where automobiles have been seen to traverse these culverts without damaging them. These tests demonstrated that safety grates meet the safety performance evaluation guidelines as specified in NCHRP Report 350 for a test level 3 (TL-3) device (Ross et al. (1992)).

Another approach is to install a guardrail on sections of roadway where high embankments are present. This approach, however, can actually increase the number and costs of crashes as the guardrail itself also creates a hazard, and is installed much closer to the roadway as compared to the culvert opening (Albuquerque, Sicking, & Lechtenberg, 2009). Although the Roadside Design Guide highlights some of the safety treatments to protect culverts, it does not specify any guidelines or conditions as to when these safety treatments should be used or which safety treatment should be chosen over others. Moreover, there have been only a few studies highlighting the guidelines for safety treatments of culverts. This provides motivation for an in-depth evaluation of culvert safety to determine those circumstances under which various treatments are warranted based on roadway and traffic conditions. This will involve a benefit-cost analysis for the various alternatives discussed above.

1.2 Research Objectives

The main objectives of this study are to determine the risk of crashes involving roadside culverts and to assess potential impacts of installing various culvert safety treatments to mitigate the frequency and severity of a crash. Based upon the results of these analyses, a related objective is to evaluate the cost-effectiveness of these safety treatments. The study also involves a survey of state DOTs that highlights the current practices adopted by other transportation agencies throughout the United States regarding the protection of culverts.

1.3 Thesis structure

This thesis is organized into seven chapters. The introductory chapter provides a brief overview, background information and objectives of the study. The remaining chapters are described as follows:

Chapter 2 discusses design practices by the Federal Highway Administration (FHWA) and AASHTO Roadside Design Guide (RDG) as well as state design practices, focusing on the Iowa Department of Transportation (Iowa DOT). It also highlights important findings from a survey sent out to other state DOTs on practices adopted by them for culvert safety treatments.

Chapter 3 provides a detailed review of the existing literature on various culvert safety treatments. It also discusses in detail the practices adopted by FHWA and the Iowa DOT. In addition, it explains the incremental benefit-cost analysis used to examine the cost effectiveness of these safety treatments.

Chapter 4 summarizes the data collection methods and procedures incorporated in the study. It explains the procedures adopted for extracting the culvert-related crashes. It provides a statistical summary of data collected from various resources provided by the Iowa DOT, such as crash database, Geographical Information Management System (GIMS), and culvert database. It also provides a data summary on the severity of crashes based on the highway system.

Chapter 5 presents the methodology for calculating crash rates based roadway classification. It also provides a detailed description of the Roadside Safety Analysis Program (RSAP), which was utilized to determine crash costs of being involved in a crash with culvert based on different roadway and traffic conditions. The costs associated with the installation and maintenance of culverts, guardrails and safety grates are covered in this chapter.

Chapter 6 presents the results of the analyses. This includes the analysis of crash rates for different types of roadways as well as the benefit-cost analyses results from RSAP for different highway scenarios and culvert sizes created.

Chapter 7 summarizes the key findings and conclusions from the project. Additionally, it highlights some of the limitations and shortcomings of the project and discusses the future research that could be done regarding the safety treatments of culverts.

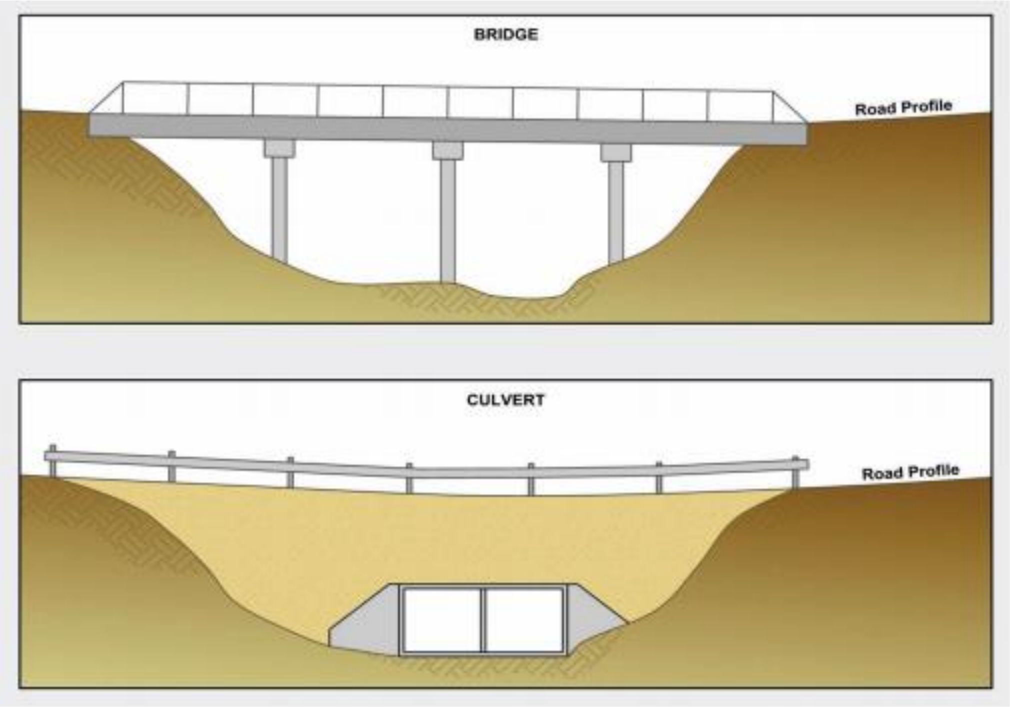
CHAPTER 2. STATE-OF-THE-ART/PRACTICE REVIEW

This chapter highlights design practices by the Federal Highway Administration (FHWA) and AASHTO Roadside Design Guide (RDG) as well as state design practices, focusing on the Iowa Department of Transportation (Iowa DOT). It also highlights important findings from a survey sent out to other state DOTs on practices adopted by them for culvert safety treatments.

2.1 National Design Practices

The Federal Highway Administration (FHWA) has specified guidelines for planning and hydraulic design of culverts (FHWA, 2012). The design of a culvert depends on many diverse factors to be taken into consideration such as hydraulic design, proper location and alignment, channel stability, minimization of maintenance requirements, debris loading, life cycle costs, etc.

The first consideration is whether a culvert or a bridge is required at a given roadway location as shown in Figure 2.1. Culverts are installed where bridges are not hydraulically required and when it is more economical to put culvert rather than a bridge. Bridges are required when it is not possible to have a culvert at that location and where environmental concerns are not satisfied by installing a culvert. The initial cost of a culvert is much less than that of a bridge since culvert installations have a smaller opening. Maintenance costs for a culvert involve channel erosion at inlet and outlet, deterioration of the culvert invert, sedimentation, and debris accumulation. Maintenance costs for a bridge involve maintenance of the bridge deck and superstructure, erosion around piers, and debris accumulation. Bridge maintenance is usually costlier. According to the National Bridge Inspection Standards (NBIS), any culvert that exceeds a span of 20 feet is considered a bridge. This classification ensures that the culvert will be inspected as part of the bridge inspection program, although it does not affect the design of the culvert.

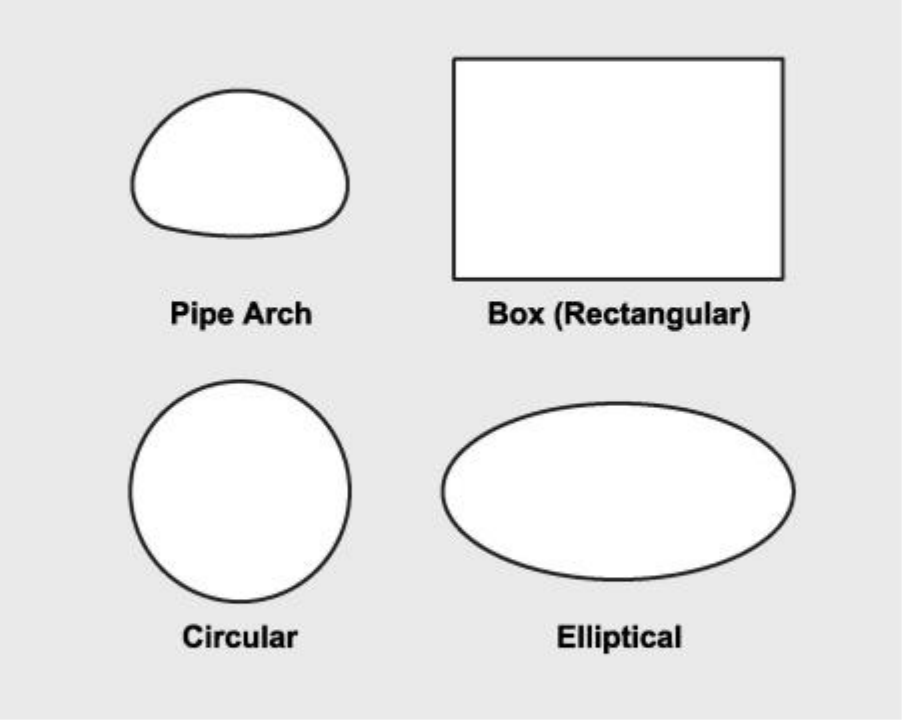


Source: FHWA (FHWA, 2012)

Figure 2.1 Bridge vs. Culvert

Safety and hydraulic considerations also affect the choice of a culvert or a bridge. The safety consideration for a culvert includes the installation of guardrails or longitudinal grates. There are varied differences in the hydraulic assumptions for a culvert and a bridge. For culverts, it is usually assumed that the flow velocity is negligible, which overestimates the energy losses. For bridges, the hydraulic analysis is based on varied flow calculations, thereby providing a better and more accurate water surface profile.

Culverts come in different shapes and sizes and are made from a variety of materials such as concrete, corrugated metal (aluminum or steel), and plastic (high-density polyethylene (HDPE) or polyvinyl chloride (PVC)). The material selection depends on the required structural strength, durability and constructability. For highways and interstates, concrete culverts are preferred whereas for driveways, corrugated pipe culverts are mostly used. The most common shapes are box, circular, pipe arch, and elliptical as shown in Figure 2.2. The shape selection is based on the cost of construction, embankment height, and the upstream water surface elevation. Box (rectangular) culverts are generally preferred for larger sizes.



Source: FHWA (FHWA, 2012)

Figure 2.2 Commonly used cross-sectional shapes for culverts

The hydraulic capacity of a culvert can be improved by appropriate inlet selection. The inlet configuration selection depends on the shape, size, and material of the culvert to be used as well as the hydraulic performance, structural stability and erosion control. Inlets can be pre-constructed or can be constructed in place depending on the environmental and geometric restrictions. Generally, the preferred inlets are projecting barrel, standard end sections, cast-in-place concrete headwalls, and ends mitered to slope, as shown in Figure 2.3. Standard end sections are the preferable treatment for interstates and other major highways.

Source: FHWA (FHWA, 2012)

Figure 2.3 Inlet types for culverts

In regard to the protection of these culverts from errant vehicles, the AASHTO Roadside Design Guide (RDG) has specified some safety treatments. A detailed description of each of these safety treatments is discussed in literature review.

2.2 Existing State Design Practices

The following section discusses the existing design practices in effect in Iowa for small (pipe) as well as large (box) culverts. The Office of Bridges and Structures determines the design of these structures. Within this office, the preliminary bridge design section handles the layouts and design for culverts and associated structures. Information for culverts that require final design is assembled and a preliminary situation plan is developed which then is passed on to a designer for the final plan and structural design. In case of pipe culverts, this section develops the plans and layouts in detail so that the Office of Design can use the information as a reference on their final road plans (Iowa DOT, 2018a).

The development of these plans involve various steps such as analyzing hydrology and hydraulics as well as road geometry, determining the physical properties (type, size and location) of the structures, attending field reviews, and coordinating with other offices. Although the Office of Bridges and Structures prepare plans, these plans must be coordinated with other offices associated with the project since the culvert plans must fit in with the plans prepared by the Office of Design.

One of the tasks of utmost importance while constructing rural highways in Iowa is the minimal diversion of surface water. If possible, water entering the proposed right of way should be carried through the highway embankment and discharged in the same ditch. It is not always possible to leave the watershed unchanged, but it is always advisable to stick to “minimal diversion” as far as possible. Generally, a 10% increase in watershed area is acceptable due to diversion (Iowa DOT, 2018a).

A minimum allowable cover is advised by the Iowa DOT for all types of culverts. It ranges from one foot for entrance culverts to two feet for all concrete and metal pipes, keeping in mind that it is measured from the edge of the shoulder. For divided roadways, the minimum cover for culvert is one foot for the median. For precast Reinforced Concrete Boxes (RCBs), minimum cover from the edge of the shoulder is two feet, however, less than two feet cover is allowed in case of cast-in-place RCBs.

As for the pipe sizes, concrete pipe culverts generally range from 18 to 84 inches in six-inch increments. This provides enough opening for maintenance operations and reduces the risk of the culvert becoming plugged with debris. For median pipe culverts on divided highways, the minimum advisable size is 24 inches.

Regarding the culvert type, the Iowa DOT specifies that a concrete pipe should be used if a highway has more than 3000 ADT or if the highway is part of the National Highway System (NHS), including county or city roadways. For highways less than 3000 ADT that are not part of the NHS, the culvert type used shall be Unclassified Roadway Pipe (Coated CMP or HDPE Pipe). For extension of a concrete pipe culvert or small box culvert, the extension should be bid as a concrete pipe regardless of ADT.

2.3 Survey

2.3.1 Background

A questionnaire was sent to hydraulic design experts, geometric design experts, and roadway safety experts across the U.S. to identify current practices for run-off-road protection at large culverts. The questions in the survey were related to culverts installed perpendicular or diagonal to the highway (excluding culverts parallel to the highway such as those under driveways or side road crossings, as this was beyond the scope of this study). The survey was conducted through internet distribution and response and was approved exempt by the Institutional Review Board (IRB) at Iowa State University.

2.3.2 Results

Out of 90 questionnaire surveys distributed across all 50 states, 18 complete responses were recorded, all of them by state DOTs. Figure 2.4 shows a map of all the states that participated in the survey.

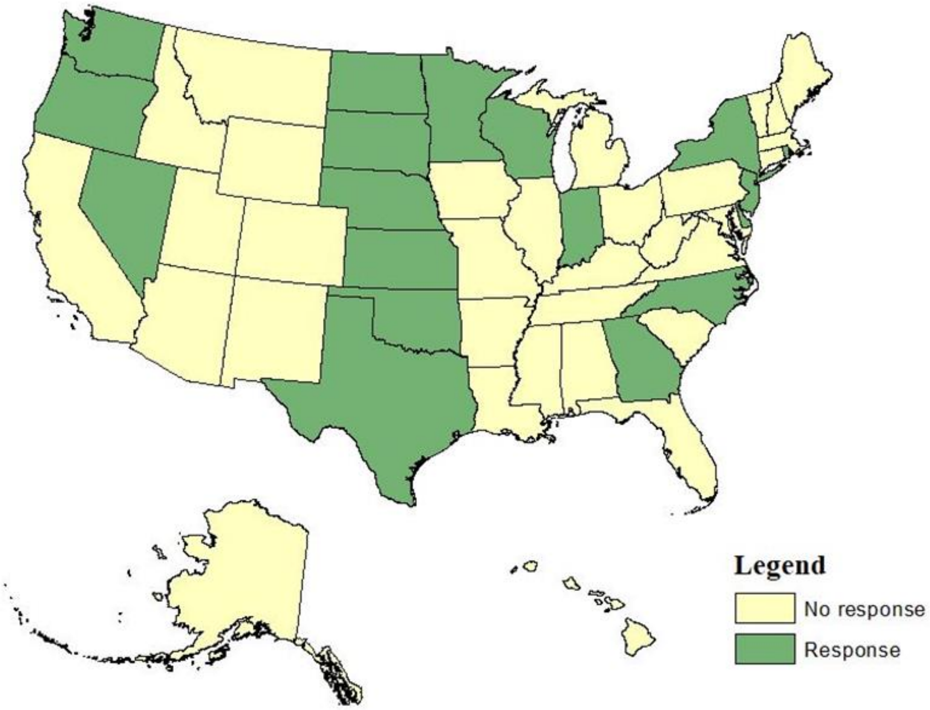


Figure 2.4 States that participated in the survey

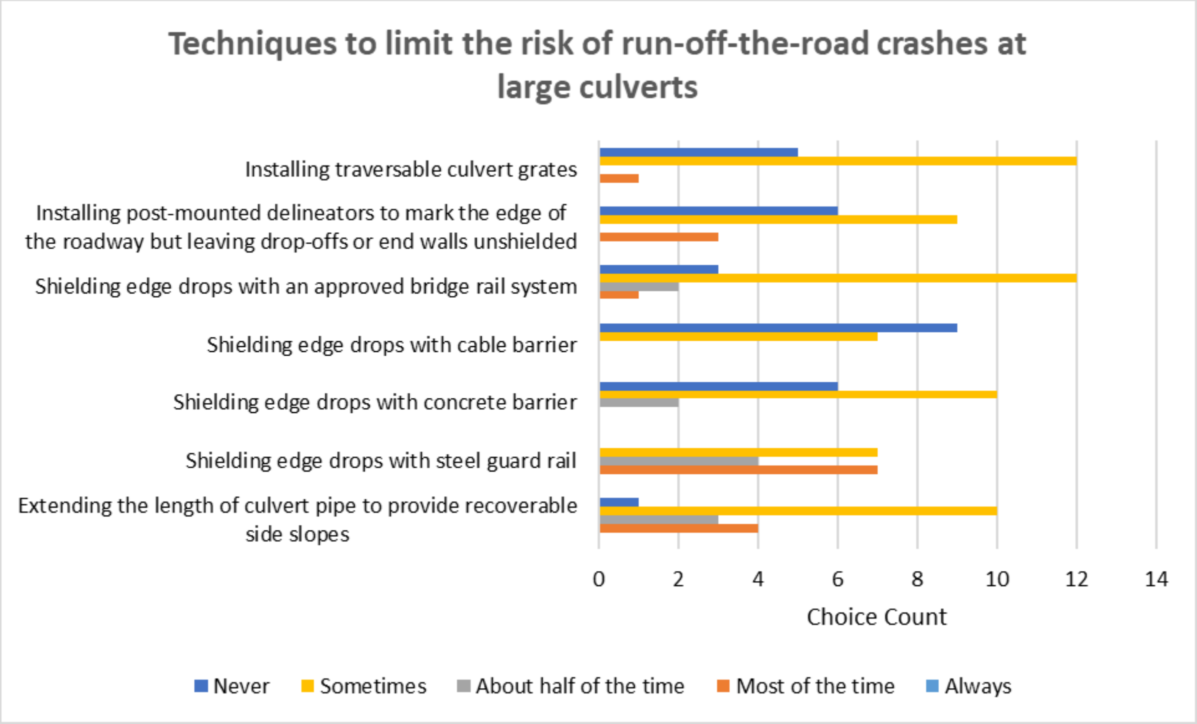


Figure 2.5 Selection of techniques to limit the risk of run-off-road crashes at large culverts

As can be seen from Figure 2.5, the most common choice to limit the risk of run-off-the-road crashes is to shield edge drops with steel guardrail or extend the length of the culverts to provide recoverable side slopes, followed by either installing traversable culvert grates or shielding edge drops with an approved bridge rail system.

One of the respondents mentioned that the preferred method would be to locate the culvert drop off outside the clear zone, but that is not possible in many situations. In that case, shielding the culvert is preferred. From the comments provided in the survey responses, it is clear that safety issues related to culverts are quite common and are highly site-specific, requiring considerable engineering judgement to determine the best alternative.

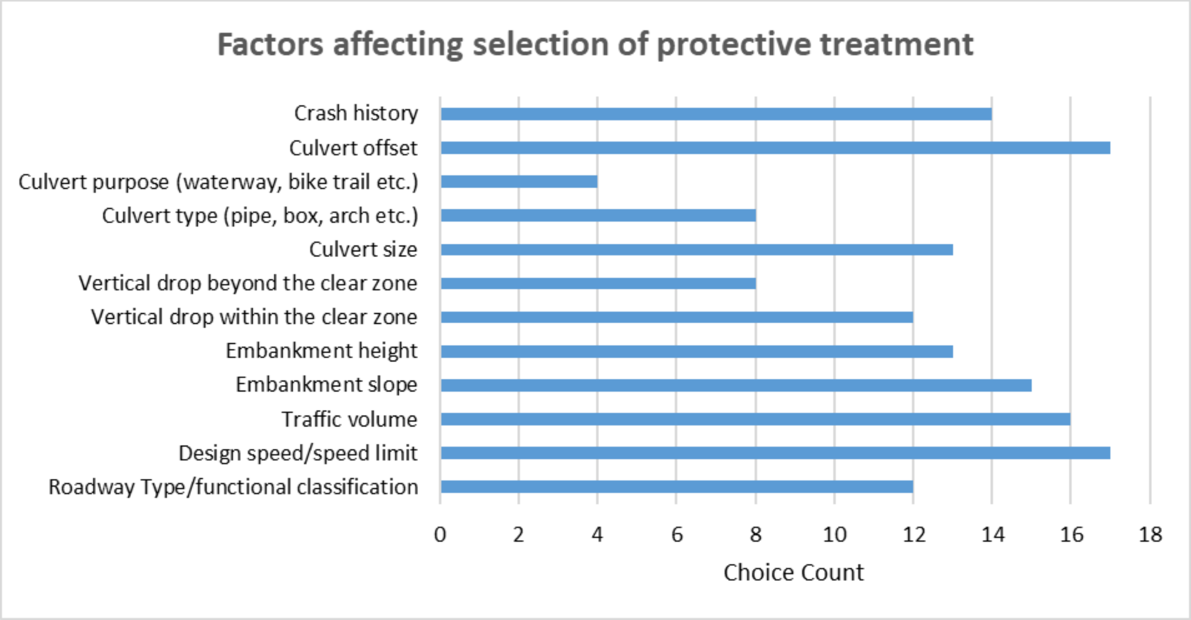


Figure 2.6 Factors affecting selection of protective treatment

Twelve out of eighteen state DOTs responding to the survey mentioned that they have some kind of written policy that indicates when to provide run-off-the-road protection for culverts. Most of these policies are stated in state design manuals. Figure 2.6 shows the factors highlighted by the respondents that affect the selection of protective treatment. The major factors include design speed/speed limit, lateral offset from the edge of the traveled way to culvert opening, traffic volume, embankment slope, crash history, culvert size, and embankment height.

CHAPTER 3. LITERATURE REVIEW

This chapter provides a detailed review of the existing literature on various culvert safety treatments. It also discusses in detail the practices adopted by FHWA and the Iowa DOT. In addition, it explains the incremental benefit-cost analysis to examine the cost effectiveness of these safety treatments.

3.1 Culvert Opening Safety Treatments

The existing preferred options for treating a culvert opening are:

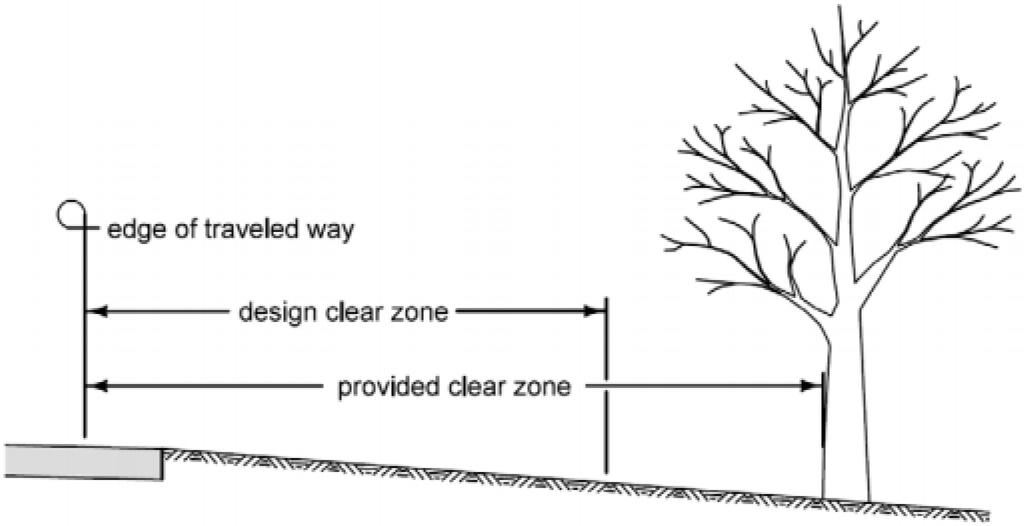
a) Eliminating the opening

b) Extending or relocating the culvert beyond the clear zone

c) Treating the opening to make it traversable

d) Shielding the culvert opening if the above options are not feasible

It is advisable to analyze the culvert opening for risk potential if the culvert is located within the clear zone. A clear zone is defined as an unobstructed roadside area that may be used by a motorist to stop safely or regain control of the vehicle and redirect it towards the roadway, as measured from the edge of the traveled way as shown in Figure 3.1. The clear zone is generally kept free from any roadside obstacles or hazards. Box culverts are a major concern because of the potential risk of drop off into the opening (Iowa DOT, 2017b). Therefore, culvert openings need to be treated to minimize the risk for run-off-road vehicles.



Source: Iowa DOT (Iowa DOT, 2017a)

Figure 3.1 Clear zone concept for roadside obstacles

Cross drainage culverts having diameter larger than 36 inches are generally treated by extending them beyond the clear zone. This ensures normal hydraulic functioning of the culvert and reduces the risk of run-off-road vehicles striking the culvert. In cases where extending the culvert up to the clear zone is not possible because of right-of-way limitations or economic restrictions, shielding the culvert opening with guardrail or safety grates is preferred. Generally, use of safety grates as specified in Standard Road Plan DR-503 (Iowa DOT, 2016a) is advisable and is useful for many sizes and shapes.

3.1.1 Culvert Extensions

The first alternative for treating a culvert is to extend it up to the edge of the clear zone. This allows the errant vehicle enough time and space to return to the travel lane. As mentioned in AASHTO's Roadside Design Guide (RDG), the width of the clear zone ranges from 2 m (7 feet) to 14 m (46 feet) depending on roadway design speed, slope, design traffic volume, and horizontal curvature, as shown in Table 3.1. Slopes steeper than 1V:3H are not recommended by the RDG.

Table 3.1 Recommended clear zone distances from edge of the traveled lane (feet)

Design Speed	Design ADT	Foreslopes			Backslopes		
		1V:6H or flatter	1V:5H to 1V:4H	1V:3H	1V:3H	1V:5H to 1V:4H	1V:6H or flatter
Less than 45 mph	Under 750	7-10	7-10	-	7-10	7-10	7-10
	750-1500	10-12	12-14	-	12-14	12-14	12-14
	1500-6000	12-14	14-16	-	14-16	14-16	14-16
	Over 6000	14-16	16-18	-	16-18	16-18	16-18
45-50 mph	Under 750	10-12	12-14	-	8-10	8-10	10-12
	750-1500	14-16	16-20	-	10-12	12-14	14-16
	1500-6000	16-18	20-26	-	12-14	14-16	16-18
	Over 6000	20-22	24-28	-	14-16	18-20	20-22
55 mph	Under 750	12-14	14-18	-	8-10	10-12	10-12
	750-1500	16-18	20-24	-	10-12	14-16	16-18
	1500-6000	20-22	24-30	-	14-16	16-18	20-22
	Over 6000	22-24	26-32	-	16-18	20-22	22-24
60 mph	Under 750	16-18	20-24	-	10-12	12-14	14-16
	750-1500	20-24	26-32	-	12-14	16-18	20-22
	1500-6000	26-30	32-40	-	14-18	18-22	24-26
	Over 6000	30-32	36-44	-	20-22	24-26	26-28
65-70 mph	Under 750	18-20	20-26	-	10-12	14-16	14-16
	750-1500	24-26	28-36	-	12-16	18-20	20-22
	1500-6000	28-32	34-42	-	16-20	22-24	26-28
	Over 6000	30-34	38-46	-	22-24	26-30	28-30

Studies conducted by Glennon (Glennon, 1974) in NCHRP Report 148 and the Minnesota Department of Transportation (Minnesota DOT, 1980) found that the highest crash rates occurred on sites with slopes steeper than 1V:3H, whereas the lowest crash rates occurred on sites with slopes of 1V:6H or less. The geometric design of the roadside also had a huge impact on the run-off-road crash rates.

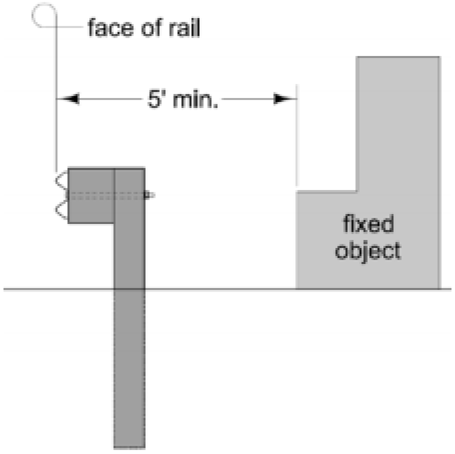
For the purpose of this project, the highest value of clear zone width within each range of design speed and design traffic volume was used. For example, for a road segment with design speed of 55 mph and design traffic volume over 6000, the average clear zone distance of 24 feet was used for a fore slope steepness of 1V:6H or flatter.

When considering all the costs involved, culvert extension might not be a good alternative. A cross-drainage culvert can be extended out of the clear zone by making the embankment flare at a higher rate, which would decrease the crash risk to a great extent.

3.1.2 Steel Beam Guardrail

Historically, many different kinds of barriers have been used to protect culverts, including angle-iron systems, wood post-and-beam systems, and concrete post-and-beam system configurations (Schrum, Lechtenberg, Stolle, Faller, & Sicking, 2012). Many of these barrier systems, however, are too weak to protect run-off-road vehicles from penetrating the barrier and striking the culverts. In some cases, these barriers pose even a greater threat than leaving the culvert opening unprotected.

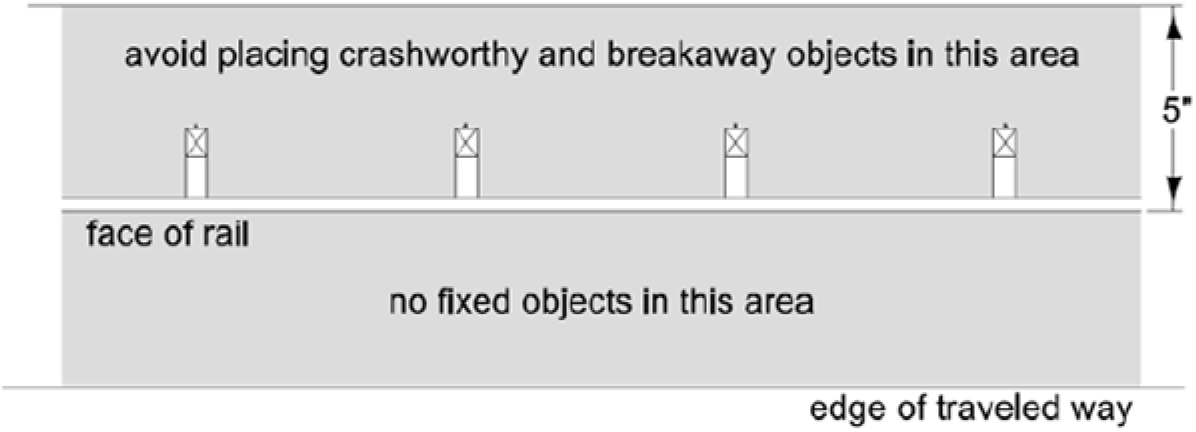
One of the most common used barriers to protect roadside obstacles is the steel beam guardrail. According to Section 8C-2 of the Iowa DOT Design Manual, the Iowa DOT uses the Midwest Guardrail System (MGS) at a mounting height of 31 inches. The steel beam guardrail is a semi-rigid barrier, which implies that the barrier deflects up to a certain extent. During a crash, the steel beam guardrail can deflect up to as much as 4 feet. Therefore, it results in higher crash forces than a flexible barrier such as a cable guardrail. A distance of at least 5 feet should be provided (Iowa DOT, 2017c) between the guardrail and a fixed object, as shown in Figure 3.2.



Source: Iowa DOT (Iowa DOT, 2017c)

Figure 3.2 Guardrail placement near a fixed object

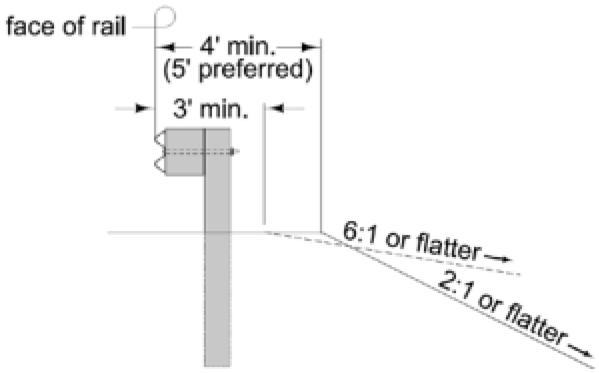
As much as possible, guardrail terminal ends should not be placed near the fixed objects as shown in Figure 3.3. This includes breakaway sign posts and light poles. The best solution to this problem is to place the guardrail end terminal upstream of the fixed objects.



Source: Iowa DOT (Iowa DOT, 2017c)

Figure 3.3 Placement of fixed objects behind guardrail

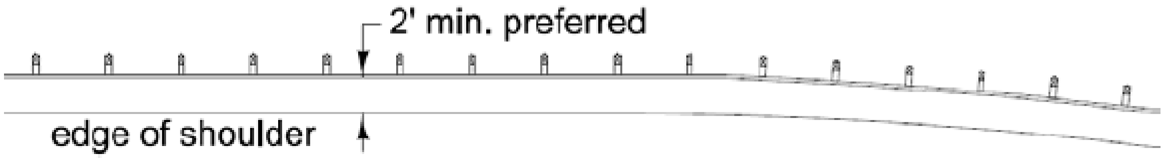
Generally, it is advisable to place guardrails on foreslopes of 10:1 or flatter. However, guardrails can be placed on foreslopes 2:1 or flatter with a minimum gap of 4 feet (5 feet preferred) between the slope and face of guardrail. This minimum gap can be reduced to 3 feet for foreslopes 6:1 or flatter as shown in Figure 3.4.



Source: Iowa DOT (Iowa DOT, 2017c)

Figure 3.4 Guardrail placement near foreslopes

Another term to be kept in mind while installing a guardrail is the guardrail offset. An offset is defined as the distance of the front face of the guardrail from the edge of the traveled way. In general, a minimum of 2 feet plus the width of the shoulder (or 2 feet from the edge of the shoulder) is preferred as the guardrail offset as shown in Figure 3.5. This is different from the "shy-line offset" (L_S), which is the offset distance beyond which an object will not be perceived by drivers as a hazard. In general, the guardrail offset should be greater than the shy-line offset. Table 3.2 shows the shy-line offset values as suggested by AASHTO RDG.



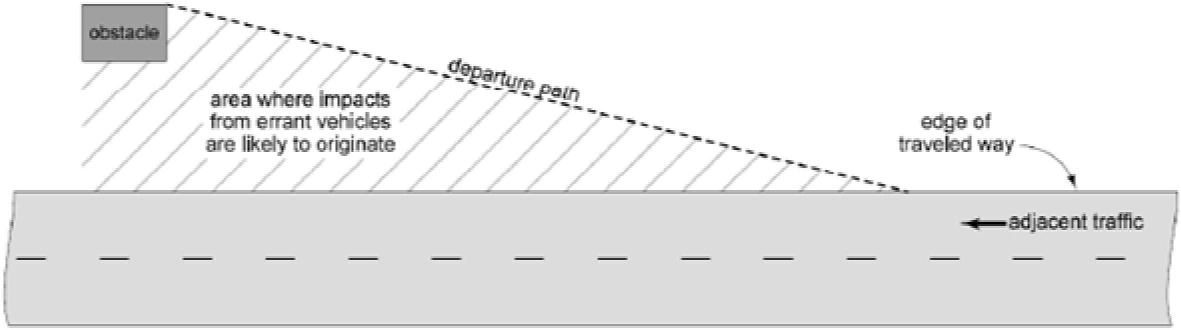
Source: Iowa DOT (Iowa DOT, 2017c)

Figure 3.5 Guardrail offset from the edge of shoulder

Table 3.2 Suggested shy-line offset for guardrails

Design Speed (mph)	**Shy Line Offset (L_S) (feet)**
20	2.5
25	3.0
30	4.0
35	4.5
40	5.0
45	6.0
50	6.5
55	7.0
60	8.0
70	9.0
75	10.0
80	12.0

The length of a guardrail should be sufficient to protect the fixed hazard or obstacle. These segments can be installed either as straight/tangent sections or as flared sections. Flared sections are generally tapered away from the roadway at a 10:1 rate. Before establishing the guardrail Length of Need (LON), it is essential to determine the area from where an errant vehicle can originate. A theoretical line known as the vehicle departure path defines this area, as shown in Figure 3.6. The location of this path is essential to determine the length of barrier needed to shield the obstacle. The guardrail offset also has a huge impact on the guardrail LON for that barrier. The farther a barrier is located from the edge of the roadway, the shorter the length will be.



Source: Iowa DOT (Iowa DOT, 2011)

Figure 3.6 Vehicle departure path and its associated area

The RDG defines a formula to calculate guardrail LON. This formula is also used by the Iowa DOT:

$$X = \frac{L_h + \left(\frac{b}{a}\right) L_1 - L_2}{\left(\frac{b}{a}\right) + \left(\frac{L_h}{L_r}\right)} \quad (1)$$

Where

X = Guardrail Length of Need (LON)

L_a = Lateral distance from the edge of the traveled way to the far side of the obstacle

L_c = clear zone width, measured from the edge of the traveled way

L_h = smaller of L_a or L_c

$a: b$ = flare rate, if present

L_1 = tangent length of the barrier measured from the upstream end of the obstacle, if a flare in standard section is used

L_2 = guardrail offset, as measured from the edge of the traveled way

L_r = Runout length

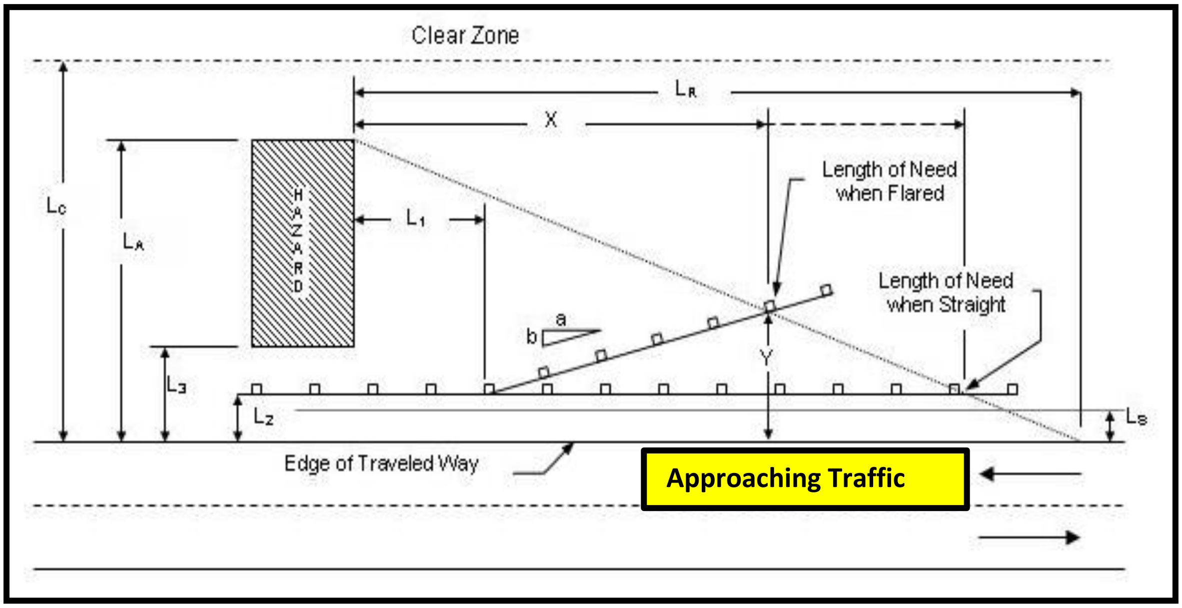


Figure 3.7 Guardrail LON for approaching traffic

Flares are used in a guardrail to decrease crash frequency by locating the guardrail farther from the traveled way, and to decrease the costs of guardrail installation by reducing the LON. For simpler calculations, it was decided to only use tangent sections for installing guardrails (Albuquerque et al., 2009). Therefore, Equation (1) can be modified as:

$$X = \frac{L_h - L_2}{\left(\frac{L_h}{L_r}\right)} \tag{2}$$

The runout length is defined as the theoretical distance needed by an errant vehicle that has left the roadway to come to a stop before hitting a roadside obstacle. It is measured from the upstream end of the obstacle to the point where a vehicle is assumed to leave the roadway as shown in Figure 3.7. These values vary based on speed limit and traffic volume, as shown in Table 3.3.

Table 3.3 Runout length table for guardrails

Design Speed (mph)	**Traffic Volume**			
	ADT ≥ 10000	**5000 ≤ ADT < 10000**	**1000 ≤ ADT < 5000**	**ADT < 1000**
	L_R (ft)	**L_R (ft)**	**L_R (ft)**	**L_R (ft)**
70	360	300	260	220
60	260	210	180	170
50	210	170	150	130
40	160	130	110	100
30	110	90	80	70

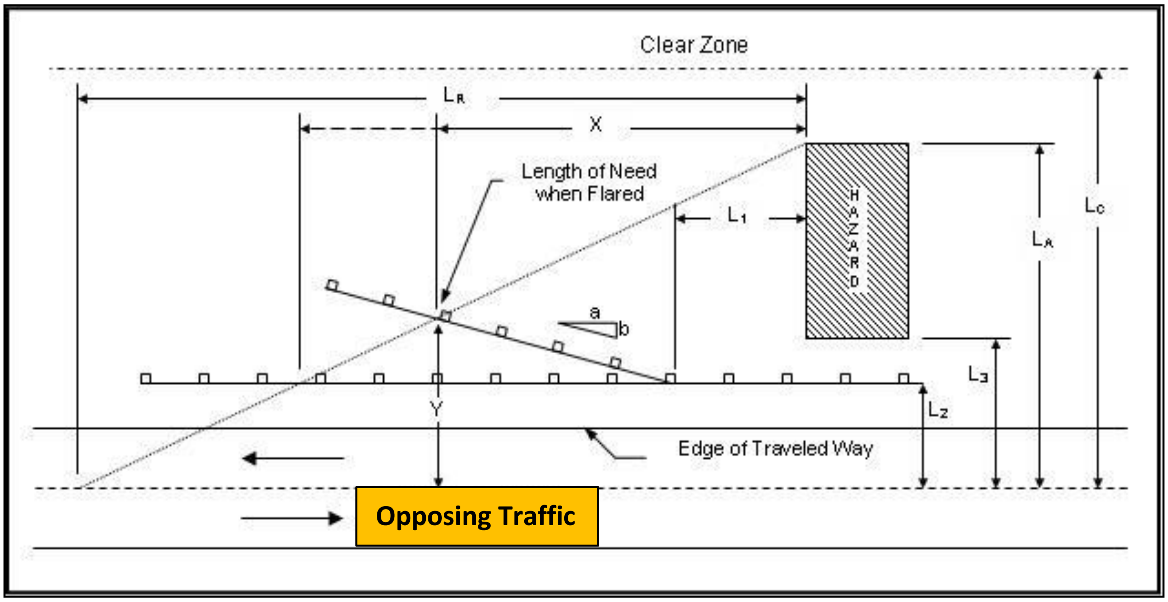
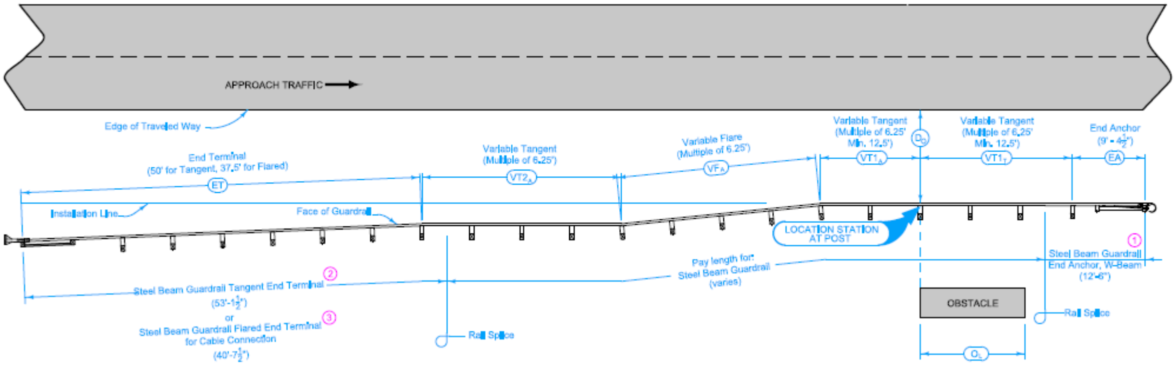


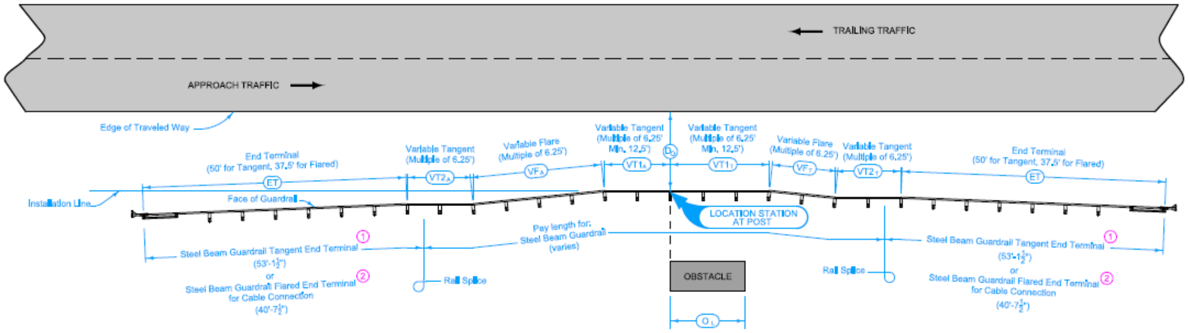
Figure 3.8 Guardrail LON for opposing traffic

Equation (2) is used for both the upstream and downstream lengths of guardrails, the only difference being that an additional lane width (12 feet) is considered while calculating L_a from edge of the traveled way to the far end of the roadside obstacle for downstream or opposing traffic guardrail, as shown in Figure 3.8. The LON for guardrails were calculated using this equation in a macro-enabled excel sheet provided by FHWA (FHWA, 2018).



Source: Iowa DOT (Iowa DOT, 2016c)

Figure 3.9 Steel beam guardrail installation at side obstacle (One-way protection)



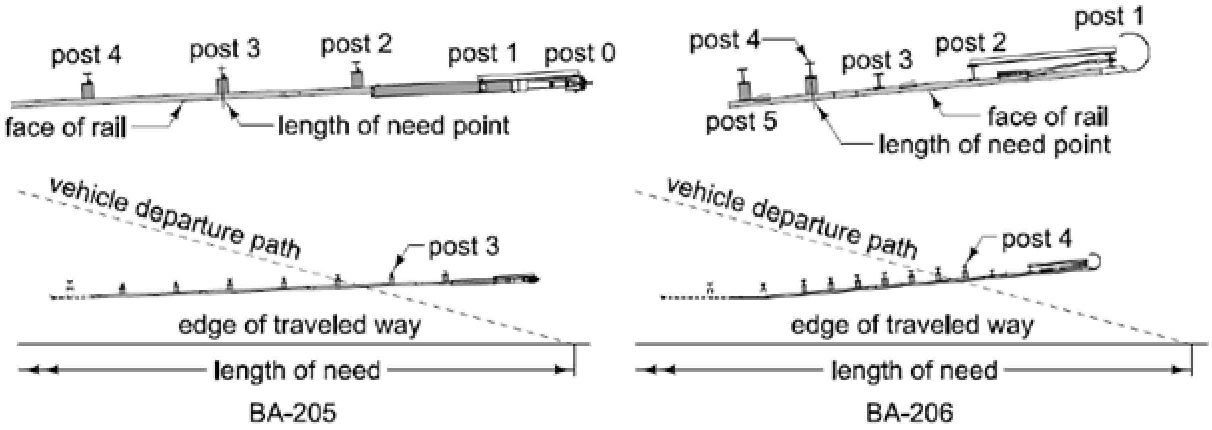
Source: Iowa DOT (Iowa DOT, 2016d)

Figure 3.10 Steel beam guardrail installation at side obstacle (Two-way protection)

At the ends of the guardrails, guardrail end terminals are placed according to standard road plans provided by the Iowa DOT as shown in Figure 3.9 for one-way protection and Figure 3.10 for two-way protection. These end terminals are placed on both approach and trailing ends of guardrail for two-lane roads, and on approach ends only for divided roads. . The length of the guardrail terminal sections are $53'1\frac{1}{2}$" for a tangent end terminal, or $40'7\frac{1}{2}$" for a flared end terminal (Iowa DOT, 2016d). BA-205 (Iowa DOT, 2016e) contains details on steel beam guardrail tangent end terminal (MASH TL-3) and BA-206 (Iowa DOT, 2016b) contains details on steel beam guardrail flared end terminal for cable connection (MASH TL-

3). Both types of end terminals are considered crashworthy when impacted end-on. For our study, we considered only the tangent end terminals for simpler calculations. In case of divided highways, the trailing end of the guardrail is generally provided with a guardrail end anchor (Iowa DOT, 2016c). The length of this section is 12′6".

As shown in Figure 3.11, the LON point for BA-205 is at post 3 whereas for BA-206, it is at post 4. The length of need point is the location where an end terminal becomes strong enough to deflect a vehicle. Thus, while installing a guardrail, it should be certain that the vehicle departure path crosses the guardrail beyond post 3 for BA-205 and beyond post 4 for BA-206.



Source: Iowa DOT (Iowa DOT, 2017c)

Figure 3.11 Length of need point for end terminals

3.1.3 Longitudinal Grates

Extending a cross-drainage culvert beyond the clear zone may be an expensive alternative if roadside embankments are high or if the slopes are steep. Large amounts of earthwork may be needed to redesign side slopes in the clear zone. Likewise, installing guardrail may prove to be an expensive alternative since this can increase the crash costs associated with the crash due to the guardrail proximity to the edge of the traveled way

(Albuquerque et al., 2009). Usually, long guardrail installations are needed to protect errant vehicles from striking culverts, thereby increasing the costs for guardrail treatments.

In light of these issues with culvert extension and guardrail installation, longitudinal grate installation is considered to be the safest and least costly alternative for treating cross-drainage culverts (Albuquerque et al., 2009), since the culvert ends are made to be traversable. However, it does affect the hydraulic efficiency of the culvert to some extent. Usually, the cost of installation of a grate increases with the size of the culvert. Figure 3.12 shows a commonly used safety grate for a pipe culvert.

Two full-scale crash tests were performed on a 21 × 21 feet culvert to examine the safety performance of culvert grates when installed on slopes as steep as 1V:3H (D. Sicking et al., 2008). These tests were performed under the guidelines of NCHRP Report 350, which concluded that these were acceptable safety grates as recommended by AASHTO RDG.

Photo: Hitesh Chawla (2019)

Figure 3.12 Commonly used safety grate for a pipe culvert

Table 3.4 and Figure 3.13 show the guidelines for installing longitudinal grates on cross-drainage culverts. These guidelines were developed by Ross et al. (1981) and later put in the AASHTO's Roadway Design Guide (RDG). The inside diameter of the rebar to be used depends on the span length of the culvert (either box or pipe).

Table 3.4 Suggested inside diameter for varying span lengths of grates

Span Length (feet)	**Inside diameter (in)**
Up to 12	3.0
12 – 16	3.5
16 – 20	4.0
20 or less with center support	3.0

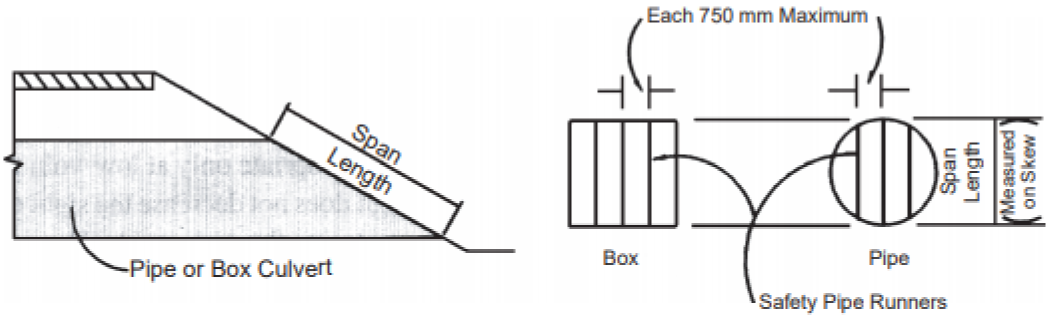


Figure 3.13 AASHTO RDG longitudinal grate guidelines

3.2 Benefit-Cost Analysis

Several studies have discussed the cost effectiveness of various roadside safety improvements for fixed objects such as culverts, guardrails, etc. (Albuquerque et al., 2009; D. L. Sicking & Wolford, 1996; Wolford & Sicking, 1997). Generally, a benefit-cost analysis is used to examine the relative cost effectiveness of two or more alternatives. The main objective of benefit-cost analysis is to select a method that prioritizes funding choices to deliver the highest return on investment. For example, a guardrail installation should provide a reasonable level of protection without increasing the number and severity of crashes, and should also have a feasible cost.

In a benefit-cost analysis, the benefits of an alternative consist of reduction in crash costs that occur when the number and severity of crashes are reduced. The direct costs involve the installation costs, annual maintenance costs, and crash repair costs of that safety treatment. The benefits are then compared to the direct costs by calculating a benefit-cost ratio:

$$\frac{B}{C} Ratio = \frac{CC_1 - CC_2}{DC_2 - DC_1} \tag{3}$$

Where

B/C ratio = Benefits-cost ratio of Alternative 2 to Alternative 1

CC_1, CC_2 = Crash costs for Alternatives 1 and 2

DC_1, DC_2 = Direct costs for Alternatives 1 and 2

A safety treatment is preferred if the expected benefits supersede the direct costs of that safety treatment, which occurs when the B/C ratio exceeds 1. If the B/C ratio is less than 1, the expected benefits are less than the expected direct costs, and the alternative is not economically viable and should not be implemented. An organization may select a higher value of benefit-cost ratio (for example, 2) to make the selection of an alternative more justifiable, since there are some inaccuracies involved in the crash cost prediction algorithm (Albuquerque et al., 2009).

Since there is a wide variation in the installation and maintenance costs of culverts and guardrails, it can be challenging to calculate general direct costs. The installation and repair costs of a culvert vary with their sizes. Data regarding the direct costs for this study were provided by the Iowa DOT and will be discussed in detail in later sections.

CHAPTER 4. DATA DESCRIPTION

This chapter summarizes the data collection methods and procedures incorporated in the study. It explains the procedures adopted for extracting the culvert-related crashes. It provides a statistical summary of data collected from various resources provided by the Iowa DOT, such as crash database, Geographical Information Management System (GIMS), and culvert database, etc. It also provides a data summary on the severity of crashes based on the highway system.

4.1 Data Collection

The first step in data collection included an extensive review to determine the extent of the information available from the Iowa Department of Transportation (DOT). This included data detailing the installation of culverts and barriers (e.g., beam guardrail), as well as detailed roadway and crash databases. The following section provides an overview of the various databases provided by the Iowa DOT, as well details of all data collection procedures that were used to collect supplementary data.

4.1.1 Roadway Database

The Iowa DOT maintains a roadway database known as Geographic Information Management System (GIMS). This database contains different datasets pertaining to roadway information. Each row in the dataset represents a segment of the roadway. For example, GIMS database for the year 2015 contains a dataset file that has the average annual daily traffic (AADT) information as well as the distribution of AADT among different vehicle class in the year 2015. Similarly, a lane dataset file contains information regarding speed limit, shoulder widths, presence of rumble strips etc. for both directions of travel lanes while a road info dataset file contains information regarding number of lanes, presence of median, median type, lane type, etc. on a particular segment. All these layers can be linked to each other using "MSLINK", which is a unique ID for every road segment present in the GIMS database. Figure 4.1 shows the accuracy of a georeferenced GIMS road segment with available aerial imagery from ArcGIS.

Figure 4.1 GIMS road segment accuracy

4.1.2 Culvert Database

The culvert dataset provided by the Iowa DOT is comprised of data collected by field staff for the primary road network (Interstate, US, and state highway systems). It contains information related to culverts such as the placement status, horizontal and vertical dimensions, length, shape, material, route on which it is installed, location (X and Y coordinates), etc. The completeness of the dataset was evaluated by mapping the culvert dataset in ArcGIS onto a map of primary road network obtained from the Iowa DOT Geographic Information Management System (GIMS) database.

A manual spatial evaluation was used to determine the percentage of road system for which reliable culvert location data existed. Around 29 percent of the data did not have any size or width information associated with it and around 27 percent of the data did not have the placement status (crossing, median or ramp culvert) of the culvert, which sometimes occurred on sizable stretches of roadway. It was unclear from the dataset whether these culverts qualified for inclusion in the study (i.e., if they were cross drainage culverts).

With the dataset provided, all the culverts on the primary road network were linked to the nearest road segment using ArcGIS. This way, all the culverts had characteristics of the nearest road segment along with the distance of the culvert to the nearest road segment. After getting the relevant culvert-related crashes, those will then be spatially joined to these culverts.

4.1.3 Barrier Database

The barrier data provided by the Iowa DOT included details of installations of steel, concrete, and cable barrier, as well as crash cushions. After getting an understanding of the details pertaining to each of the fields in the databases, ArcGIS was used to cross-reference the barrier data with the culvert data to determine the percentage of existing culverts that are being protected by any kind of barrier.

After determining the culverts that were pertinent to this study, the next step was to determine the existing barrier protection status for these culverts. The initial intent was to do this based on the steel, concrete, and cable barrier data given by the Iowa DOT; however, a quick spot check showed that the barrier datasets were incomplete or inaccurate. Therefore, a manual review was performed to determine the protection status of 8,223 culverts across the state highway network. Of these culverts, 500 (6.1%) were rejected due to either being a duplicate or were found not to exist, and 509 (6.2%) were found to be protected by a barrier of some sort. For most of the protected culverts, the primary reason for barrier installation was actually for a purpose other than protecting the culvert. For example, many culverts are protected on the left side by median cable barriers on Interstates, which were installed to reduce the risk of vehicle-to-vehicle collisions.

4.1.4 Crash Database

The Iowa DOT also keeps a record of traffic crashes across the state of Iowa. This crash database encompasses all traffic crashes in the state of Iowa that generated a police report and contains detailed information regarding these crashes. The period of analysis available for the present study was from January 2007 to August 2017 (10 years 8 months of data). After the culvert database was completed, the Iowa DOT crash database was utilized to determine how many crashes involved a culvert. The culvert-related crashes were identified using two methods:

a) The two fields “Crash sequence of events” and “First harmful Event” were filtered for the value “Culvert” in the crash database.

b) A manual search for the keywords “Culvert” and “Pipe” was performed in the database that included the police narratives of the crashes.

4.1.4.1 Crash code methodology

An exclusive crash code method was implemented as an attempt to extract culvert-related crashes from the crash database. The relevant fields used for this selection were “First Harmful Event” and “Crash Sequence of Events”. The field “First Harmful Event” describes the first event in the crash that resulted in damage or an injury and is present in the crash level file. The field “Crash Sequence of Events” describes the events for each vehicle in the order in which they occurred, which includes the first four significant events (harmful and non-harmful) in sequence. This field is recorded at the vehicle level. Both these fields were filtered for the value “Culvert” which in crash code is represented by the value “47”.

Searching on “First Harmful Event” found 1,206 crashes while searching on “Crash Sequence of Events” found 2,322 crashes. This yielded a total of 3,528 crashes. After removing duplicates, there were 2,330 culvert-related crashes across the state of Iowa. These crashes were further filtered to limit the dataset to only those occurring on the primary road network (Interstates, U.S. Highway System and State Highway System). This was accomplished by filtering on the “SYSTEM” field, wherein “1” represents Interstates, “2” represents US Highway System, “3” represents State Highway System and “4” to “9” represent other roadway types. After applying these criteria, 872 culvert-related crashes on the primary road network identified.

4.1.4.2 Crash narrative review methodology

Another method to extract culvert crashes was implemented by investigating the crash narratives as described by law enforcement officers on scene manually. A quick search on a few particular keywords was done to potentially extract target culvert-related crashes. The keywords “Culvert” and “Pipe” were used for a study period covering ten years (2007 – 2016). This gave a total of 2,133 crashes from the keyword “Culvert” and 357 crashes from the keyword “Pipe”. After identifying these 2,490 crashes, a manual data review was done to remove duplicates and false positives. As before, only crashes that occurred on primary road network were selected, using the same filtering criteria as described previously for searching on crash codes. Overall, 435 culvert-related crashes were identified by searching on crash narratives, of which 260 crashes had not been previously identified using the crash code methodology.

4.1.5 Cost Information

Cost information was needed to perform benefits-cost analyses in RSAP. The Iowa DOT provided information related to the culvert installation and repair costs, guardrail installation and maintenance costs, and safety grates installation costs. The end-section installation costs were also provided by the Iowa DOT but only for box culverts. Some costs that were obtained from other sources included maintenance costs for culverts and safety grates. These costs are discussed in detail in Chapter 5.

4.2 Data Summary

After searching on crash codes and crash narratives, a total of 1,132 culvert-related crashes were found to occur on the primary road network. Since these crashes had X and Y coordinates, they were mapped on ArcGIS, as shown in Figure 4.2. These culvert-related crashes were then spatially joined with the nearest culvert, which was already mapped to the nearest road segment. All of the attributes of the nearest culvert and nearest road segment to that culvert were thereby joined to the crash. The distance of the crash location to the nearest culvert was also calculated in this process. On closer inspection of the spatial results, some crashes were found to have a distance greater than 1 mile from the nearest culvert.

All crashes that were more than 500 m away from a culvert were disregarded, which narrowed the 1,132 crashes down to 937. There were a few reasons to choose this buffer distance as 500 m: firstly, the units of the coordinate system used in ArcGIS were meters, and secondly, 500 m was chosen visually in order to encompass as many of the crashes as realistically possible.

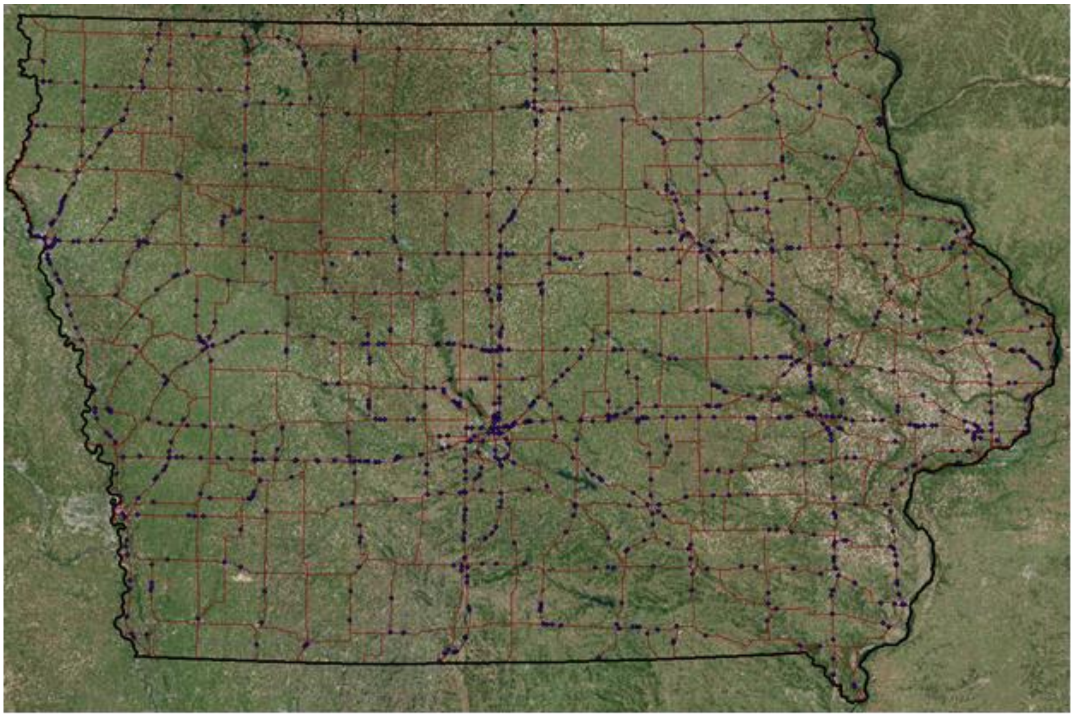
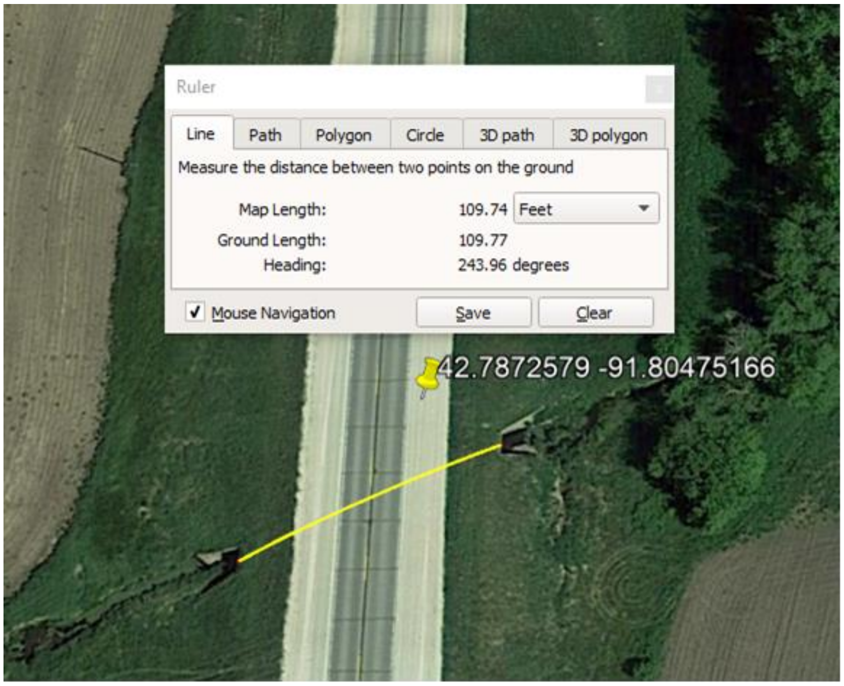


Figure 4.2 Distribution of 1,132 culvert-related crashes across Iowa

4.2.1 Culvert data summary

The combined database included both transverse and parallel culverts. Because parallel culverts are not pertinent to the present study, the attribute table was examined to identify parallel culverts using the placement field and exclude them from the analysis. Ultimately, only the crashes that were linked to a perpendicular culvert (cross-drainage culvert) from those 937 culvert-related crashes were selected for analysis. The culvert-related crash dataset after filtering based on this criterion consisted of 568 observations. The length attribute of the missing culverts in this final dataset was completed to the extent possible using the Ruler tool in Google Earth, as shown in Figure 4.3.



Measure the distance between two points on the ground

Map Length: 109.74 Feet

Ground Length: 109.77

Heading: 243.96 degrees

☑ Mouse Navigation

Figure 4.3 Length of culvert measured manually in Google Earth

Table 4.1 provides the data summary for 568 crashes that are related to 547 cross-drainage culverts. It was assumed that the center of a perpendicular culvert lies on the centerline of the roadway, which implies that the culvert offset from the centerline was taken as one-half the length of the culvert. It should be noted that since GIMS does not allow for any directional analysis, the speed limits were averaged across opposing directions of travel.

Table 4.1 Summary statistics for the 547 perpendicular (cross-drainage) culverts

Variable	**Category**	**Count**	**Percentage (%)**
Crashes		568	
Culverts		547	100.00
Shape	Round	358	65.45
	Box	164	29.98
	Arch	5	0.91
	Round/Box	15	2.74
	Box/Arch	2	0.37
	Unknown	3	0.55

Table 4.1 (continued)

Distance to nearest culvert (feet)	<100	172	31.44
	100-200	163	29.80
	200-500	150	27.42
	500-1000	43	7.86
	1000-1500	16	2.93
	>=1500	3	0.55
Length (feet)	<75	181	33.09
	75-150	226	41.32
	150-225	91	16.64
	>=225	38	6.95
	Unknown	11	2.01
Size (width)	< 4 feet	341	62.34
	4-10 feet	107	19.56
	>=10 feet	44	8.04
	Unknown	55	10.05
Speed Limit (mph)	Less than 45	18	3.29
	45-50	43	7.86
	55-60	278	50.82
	65	99	18.10
	70	109	19.93
No. of lanes	Less than 4	283	51.74
	4 or 5	242	44.24
	6 or more	22	4.02
Roadway Classification	Interstate	158	28.88
	US Highway System	207	37.84
	State Highway System	182	33.27
Culvert offset from center line (feet)	Less than 40	213	38.94
	40-80	203	37.11
	80-120	88	16.09
	>=120	32	5.85
	Unknown	11	2.01

For the purpose of this study, culverts have been divided into different categories based on their sizes and shapes. These are:

- Small pipe culverts: pipe culverts with size (diameter) less than four feet.
- Medium pipe culverts: pipe culverts with size (diameter) between four feet and ten feet.
- Medium box culverts: box culverts with size (width) between four feet and ten feet.
- Large box culverts: box culverts with size (width) greater than ten feet.

This dataset of 568 culvert-related crashes still contained some missing data. Records with missing lengths or missing culvert sizes were removed from the dataset. The final culvert dataset included 500 crashes related to 481 culverts.

4.2.2 Crash data summary

One of the most important fields in the crash data is the crash severity, which is helpful in analyzing the crash risk and benefit-cost analyses. The most commonly used scale to define crash severity is the five-point KABCO scale. This scale is frequently used by law enforcement officers for classifying injuries and can also be used to establish and assess crash costs. This five-point classification is: fatal injury (K), serious injury (A), minor injury (B), possible injury (C) and property damage only (PDO) (O) crashes. In the crash data, the crash severity is coded as 1 (one) for a fatal injury crash and 5 (five) for a PDO crash. Table 4.2 shows the summary statistics of the final dataset of culvert-related crashes based on the roadway classification, which excludes the missing values.

The three road classifications were seen to have almost same average crash severities. About 71-74 percent of crashes that occurred during the analysis period were either PDO or possible injury crashes, around 14-20 percent comprised of non-incapacitating/minor injury crashes, and 7-13 percent comprised of severe injury (fatal and serious) crashes, as can be seen from Figure 4.4.

Table 4.2 Crash severity distribution based on roadway classification

Crash Severity	Roadway Classification (%)		
	Interstate	**US Highway System**	**State Highway System**
1 – K (Fatal injury)	2 (1.5)	3 (1.6)	4 (2.3)
2 – A (Serious injury)	8 (6.0)	21 (10.9)	14 (8.0)
3 – B (Minor injury)	26 (19.4)	28 (14.6)	31 (17.8)
4 – C (Possible injury)	17 (12.7)	48 (25.0)	45 (25.9)
5 – O (Uninjured/PDO)	81 (60.4)	92 (47.9)	80 (46.0)
Total	134	192	174
Average (1-5)	4.25	4.07	4.05

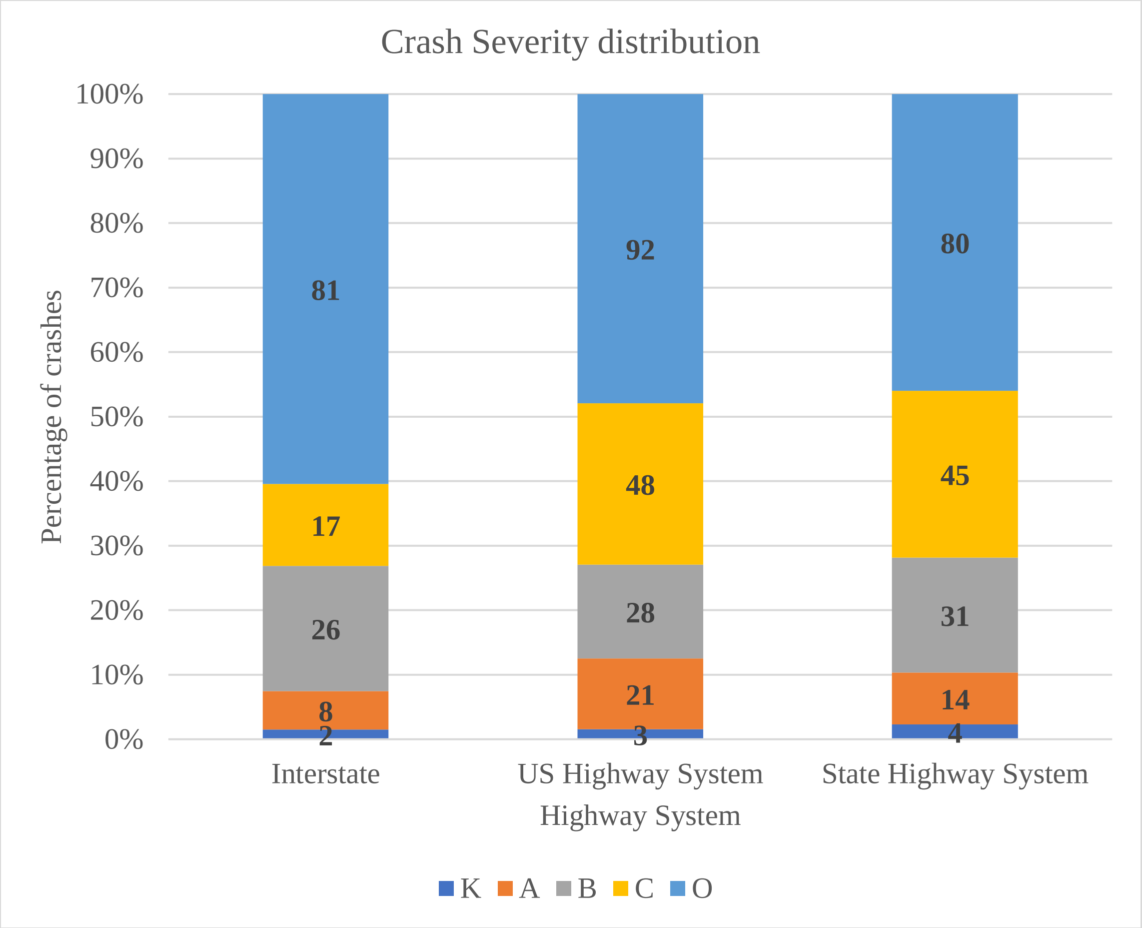


Figure 4.4 Crash severity distribution based on roadway classification

This chapter highlighted the data collection methods and procedures incorporated in the study. It explained the procedure adopted to extract culvert-related crashes and a detailed summary of the combined datasets and crash severity.

CHAPTER 5. METHODOLOGY

This chapter discusses the methods for calculating crash rates based on different classifications of roadway. It also provides a detailed description of the Roadside Safety Analysis Program (RSAP), which was utilized to determine crash costs for culvert-related crashes under different roadway and traffic conditions. The costs associated with the installation and maintenance of culverts, guardrails and safety grates are also covered in this chapter.

5.1 Crash Rate Analysis

After compiling the entire dataset for 500 culvert-related crashes, the crash rates were calculated. These were calculated using the traffic volume as the exposure variable, which was expressed as the number of vehicles crossing the culvert. The equation for calculating a crash rate on a particular segment is:

$$R_i = \frac{100{,}000{,}000 \times C_i}{365 \times N_i \times V_i} \tag{4}$$

Where

R_i = Crash rate (crashes per 100 million crossing vehicles)

C_i = Number of culvert-related crashes on that segment

N_i = Number of years in the study

V_i = Traffic volume (average AADT) on that roadway segment

The average crash rate for a particular highway system was calculated from:

$$R_i = \frac{100{,}000{,}000 \times \sum C_i}{365 \times N_i \times \sum V_i} \tag{5}$$

Where

$\sum C_i$ = Sum of crashes on all segments in that highway system

$\sum V_i$ = Sum of traffic volume (sum of average AADT) on all segments in that highway system

Since the analysis period was from January 2007 to August 2017, the number of years in the study (N_i) was set to 10.6 years. For calculating average AADT on a roadway segment, the AADT for that respective road segment was obtained from GIMS database for the years 2007 – 2016 using the field "MSLINK". These values were averaged over the respective years for which data was available.

5.2 Roadside Safety Analysis Program

Due to a limited number of culvert-related crashes that were pertinent to the study, it was required to use a simulation software to evaluate the impacts of design factors, such as traffic volume, culvert offset, truck percentage, etc. For this purpose, RSAP was used.

5.2.1 Overview

Roadside Safety Analysis Program (RSAP) is an encroachment-based software tool that performs benefit-cost analyses on various roadside design alternatives. It helps a roadside designer in choosing the best alternative by estimating the expected crash costs and performing an incremental cost-benefit analysis of different alternatives. The first version of RSAP was developed in 1988 under NCHRP Project 22-09 and became available for public use with the 2002 edition of Roadside Design Guide (AASHTO 2002) (RoadSafe LLC, 2012b). Various releases of RSAP have been distributed with the AASHTO Roadside Design Guide (RDG) since the 2002 edition. The latest version of RSAP (RSAPv3), which was developed under NCHRP Project 22-27, incorporates the same basic cost-effectiveness analyses but also includes the ability to add new special hazards such as bodies of water and edges of median and a new probability of injury method for estimating crash severity.

RSAPv3 uses a conditional encroachment-collision severity approach to estimate the frequency, severity and societal cost of roadside crashes for each of the alternatives designed in the software. For every alternative, the agency costs (construction and maintenance costs) are provided to the software. The alternative that results in the largest reduction in crash costs (benefits) compared to the agency costs for improvement (i.e., having the highest benefit to cost ratio) is considered the “best” alternative. Any analysis in RSAP is based on a series of conditional probabilities, which are computed through the following four modules: encroachment probability module, crash prediction module, severity prediction module and benefit/cost analysis module.

First, the software predicts the expected number of encroachments on the basis of traffic and geometric characteristics of the roadway using the encroachment prediction module. After an encroachment has occurred, the crash prediction module determines the likelihood of that encroachment resulting in a crash. If that encroachment is likely to result in a crash, the third module evaluates the severity of that crash. Finally, the benefit/cost module converts those severities into dollar estimates to calculate and compare reduction in crash costs (benefits) to the direct/agency costs (costs) of that alternative (RoadSafe LLC, 2012b).

5.2.1.1 Encroachment probability module

The encroachment probability module estimates the number of encroachments that can be expected on a particular road segment using a two-step process. The first step is to calculate the expected number of encroachments based on the baseline conditions. The second step involves applying the relevant adjustment factors based on the road type to account for modifications from the baseline conditions. These factors account for differences in number of lanes, posted speed limit, access density, terrain, vertical grade, horizontal curve and lane width from the baseline conditions.

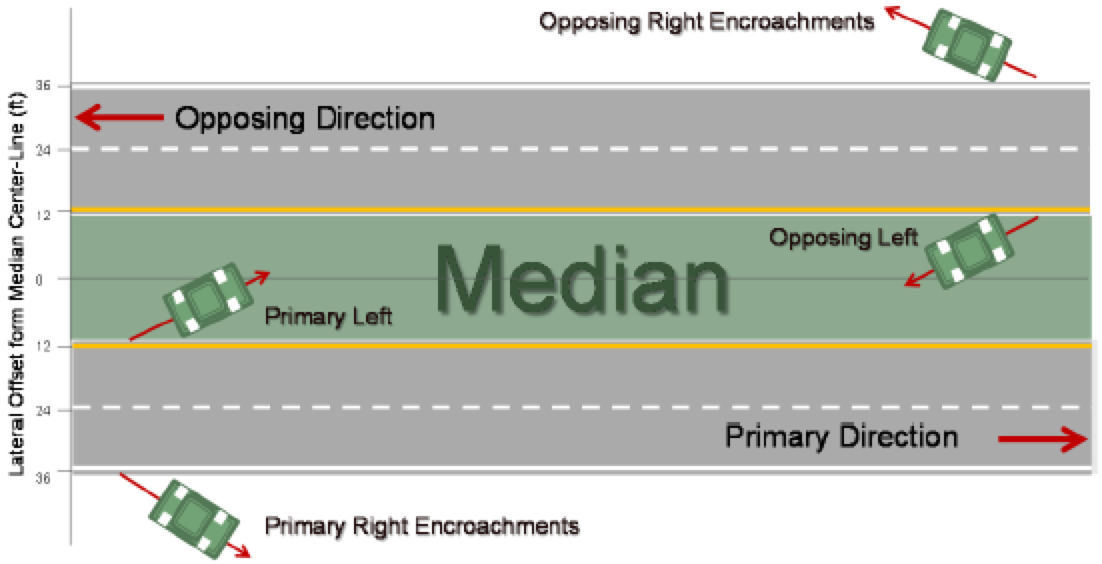
RSAPv3 defines highway types as four-lane divided, two-lane undivided and one-way highways. Cooper (1980) estimated the default values for baseline condition, which were derived from extensive data collection and analysis on different highway types and traffic volume (AADT) (Cooper, 1980; RoadSafe LLC, 2012b). The base conditions for these encroachment frequencies are:

- Posted speed limit = 65 mph
- Flat (level) terrain
- Relatively straight segments
- Lane width greater than or equal to 12 feet
- Zero major access points per mile.

A four-lane divided highway consists of traffic moving in two directions (primary and opposing), separated by a median. Each direction has two encroachment possibilities, left side and right side. Therefore, the total possible encroachments for a divided highway are:

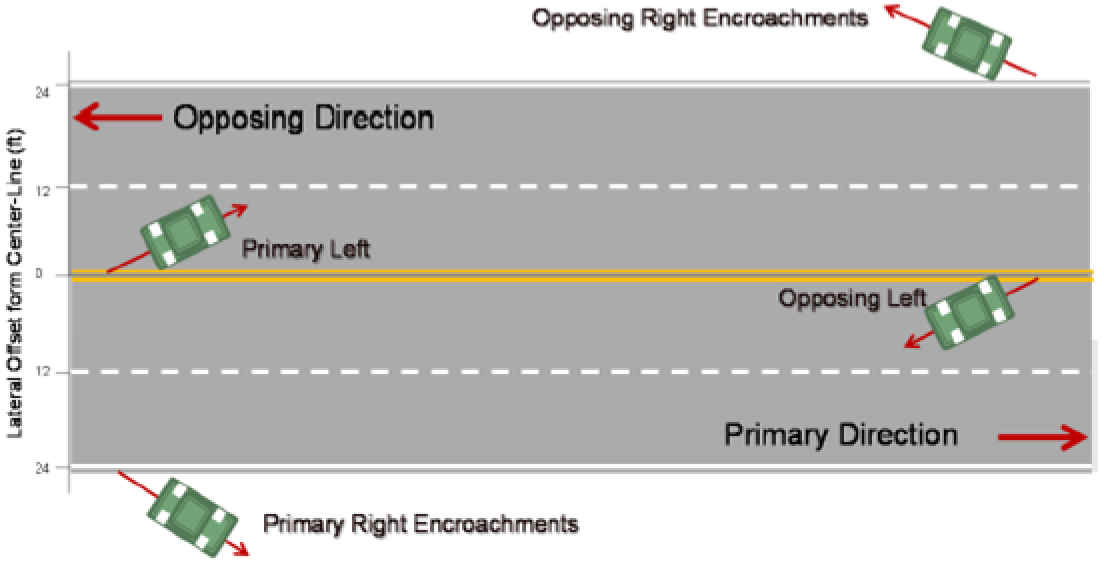
a) Primary direction right encroachment
b) Primary direction left encroachment
c) Opposing direction right encroachment
d) Opposing direction left encroachment

For a two-lane undivided highway, the possible encroachments are the same as those for a divided highway. Figure 5.1 and Figure 5.2 illustrate the four possible encroachments for a four-lane divided and two-lane undivided highway respectively.



Source: (RoadSafe LLC, 2012c)

Figure 5.1 Possible encroachments for a four-lane divided highway



Source: (RoadSafe LLC, 2012c)

Figure 5.2 Possible encroachments for a two-lane undivided highway

The encroachment in each direction was estimated by multiplying the directional distribution of the traffic and left/right encroachment split to the encroachment frequency. The default values for both directional split and encroachment split are 50-50 but can be changed based on the actual data. For a one-way highway, it is assumed that they have same functional characteristics as those of four-lane divided highways, but the encroachment frequency is halved to account for the assumption that all the traffic is assigned to the primary direction.

5.2.1.2 Crash prediction module

Once the encroachment probability is determined, the next step is to determine the probability of a particular encroachment resulting in a crash. This is achieved by projecting the vehicle trajectories onto the roadside hazards. Three types of roadside hazards are included in RSAPv3, namely, point, line, and area hazards. Point hazards include utility poles, trees, signs, etc. whereas line hazards generally include guardrails, cable barriers, concrete barriers, etc. Area hazards are related to terrain features like slopes and ditches and generally involve vehicle rollover. While running an analysis in RSAPv3, the point and line hazards are constructed in different alternatives to create a real-life scenario of the roadway.

The trajectory database used by RSAPv3 was created under NCHRP Project 17-22, which generated a run-off-road (ROR) crash reconstruction database from 890 crash cases (RoadSafe LLC, 2012b). Based on the characteristics defined for the roadway segment, RSAPv3 searches for all the trajectories from the database that lie within an acceptable range of defined characteristics. RSAPv3 recognizes four different characteristics as a base to its selection of various vehicle trajectories:

- Roadside cross-section profile (weight assigned = 3)
- Horizontal curve radius (weight assigned = 2)
- Highway vertical grade (weight assigned = 1)
- Posted speed limit (weight assigned = 1)

The roadside cross-section profile is believed to have the highest influence on vehicle trajectory, followed by horizontal curve radius, vertical grade, and posted speed limit, in that order (RoadSafe LLC, 2012b). RSAPv3 uses a basic methodology for selection of trajectories that involves examining and scoring each trajectory based on a quantitative comparison of the four roadway characteristics mentioned. These scores are then combined into a single composite score based on the weighted average of the four individual scores for each trajectory, and the trajectories with the highest composite scores are selected for use in the analysis. A good agreement is awarded for a score of 0.93 or higher by RSAPv3 and is used for analysis.

After the selection of desirable vehicle trajectories, each trajectory is mapped at the beginning of the road segment and at pre-defined equal intervals along the user-defined roadway to determine the probability of a crash resulting from an encroachment. Three possible outcomes can happen when a collision occurs: complete stop, hazard penetration, or vehicle redirection. In case of hazard penetration or redirection, the vehicle trajectory is examined further to determine the possibility of rollover or striking other hazards.

5.2.1.3 Severity prediction module

The severity prediction module determines the likely average severity of the crash, which in turn is useful in determining the average crash costs. RSAPv3 uses a Severity Index (SI) unique to each roadside hazard to represent the severity of striking it, as described in NCHRP Report 492. The development of a crash severity model for each hazard involves the estimation of following three parameters: a value that indicates the severity of a crash when collisions do not result in penetration or redirection, a percentage of the total crashes that result in penetration or rollover event due to the barrier, and a percentage of crashes for which a rollover event occurs after barrier redirection.

An equivalent fatal crash cost ratio (EFCCR) is estimated within RSAPv3, which is a measure of the severity of each likely crash. EFCCR is a dimensionless measure of crash cost that can be scaled to any particular year, assuming the underlying distributions of severity remain constant. It is obtained by dividing the average crash cost for each SI severity distribution by the cost of a fatal crash.

5.2.1.4 Benefit/Cost analysis module

The final module performs the benefit/cost analysis. This module calculates a benefit/cost ratio for each alternative, with benefits in the numerator and agency costs in the denominator. The benefits include the reduction in crash costs for each alternative whereas the agency costs include the construction and/or maintenance costs for each alternative, as well as the cost of repairs as a result of crashes with the hazards.

The crash costs related to each crash are calculated using the FHWA economic value of life. This is a monetary estimate of the costs that individuals are willing to pay to prevent a traffic fatality. According to the FHWA, the economic value of life is approximately $9.1 million per fatality, which is the default parameter for fatal injuries in RSAPv3. For the other severity categories, a percentage of the fatal estimate is utilized. For each alternative, an annual average crash cost is calculated by summing the expected crash costs for predicted crashes. These are then normalized to an annual basis.

5.2.2 Scenarios

A wide variety of scenarios was designed in RSAP based on the data summary table from Table 4.1 and using the data provided in Table 5.1. These were:

- Two-lane undivided highways with speed limit of 55 mph.
- Four-lane divided highways with speed limit of 55 mph
- Four-lane divided highways with speed limit of 65 mph.

- Four-lane divided highways with speed limit of 70 mph.
- Six-lane divided highways with speed limit of 70 mph.

All cross-drainage culverts were divided into two categories:

a) Crossing culverts: Culverts that ran under all lanes of travel

b) Median culverts: Culverts that ran under one direction of travel. Ramp culverts were also included in this category since ramps are one-directional.

For divided highways, crossing culverts and median culverts were designed separately. In addition, each category of highways defined above contained four different scenarios for each culvert size category, i.e., small pipe, medium pipe, medium box and large box culverts.

Table 5.1 Project characteristics used in RSAP analysis

Characteristic	**Value**
Project Information	
Design life	20 years
Construction year	2020
Rate of return*	4%
Gross Domestic Product (GDP) Deflator*	7%
Value of Statistical Life (VSL)	$5.4 million (min.) (2015 USD) $6.2 million (2018 USD) $ 13.4 million (max.)(2015 USD)
Encroachment Adjustment*	1
Decision point benefit-cost ratio	2.0
Roadway Information	
Traffic growth rate*	1%
Terrain*	Flat
Average Annual Daily Traffic (AADT) used	Mid-life
Percent of traffic in primary direction*	50%
Lane width*	12 feet
Segment length	600 feet
Cross section used	1V:6H

*Default value of the characteristic

The design life of a culvert was set to 20 years, the value used by the Iowa DOT (Iowa DOT, 2018b). The default rate of return (discount rate) of 4% was retained, as this is the value recommended by the Iowa DOT (Iowa DOT, 2018b). RSAP User’s Manual defines the value of statistical life (VSL) as “the average comprehensive crash cost of a fatal crash” (RoadSafe LLC, 2012a). In Iowa, the cost per fatality is $4.5 million (Harmon, Bahar, & Gross, 2018; Iowa DOT, 2018b). The average occupancy per vehicle involved in any crash in Iowa between 2007 and 2016 for a vehicle having at least one occupant was 1.38. This implies that the cost per fatal crash (VSL) would be equal to $6.2 million, assuming that all occupants in fatal crashes suffer fatalities (Cyr, 2018). Two similar models were generated in RSAP to account for the recognized uncertainty of the VSL, using the recommended minimum and maximum alternative estimates of $5.4 million and $13.4 million, respectively (Cyr, 2018; Moran & Monje, 2016).

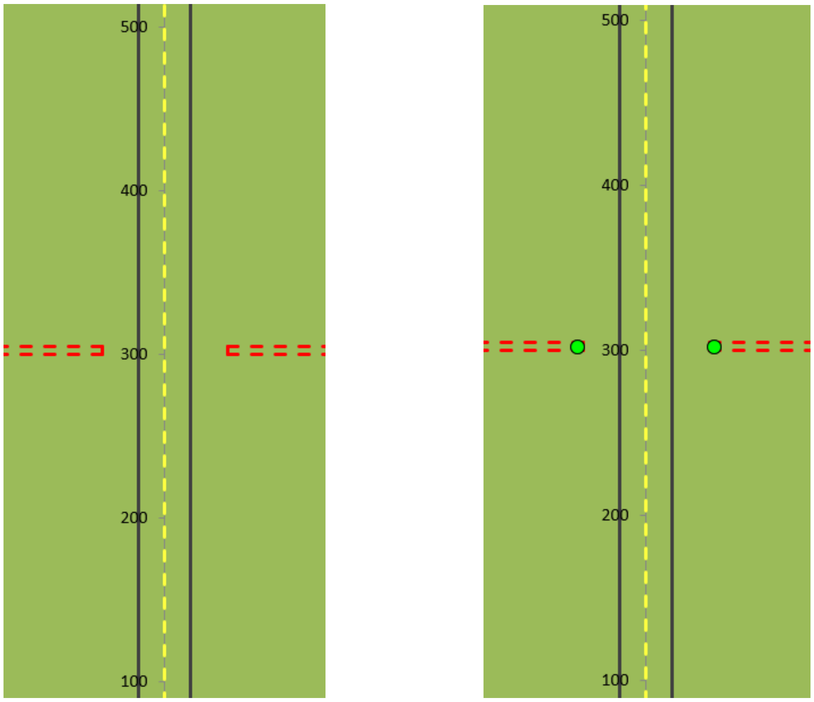
Based on manual measurements at several representative locations in Google Earth, it was decided to keep the default values for shoulder widths. These are 6 feet on both sides for undivided highways, or 6 feet and 10 feet respectively for the median and outside shoulders for divided highways.

5.2.3 Alternatives

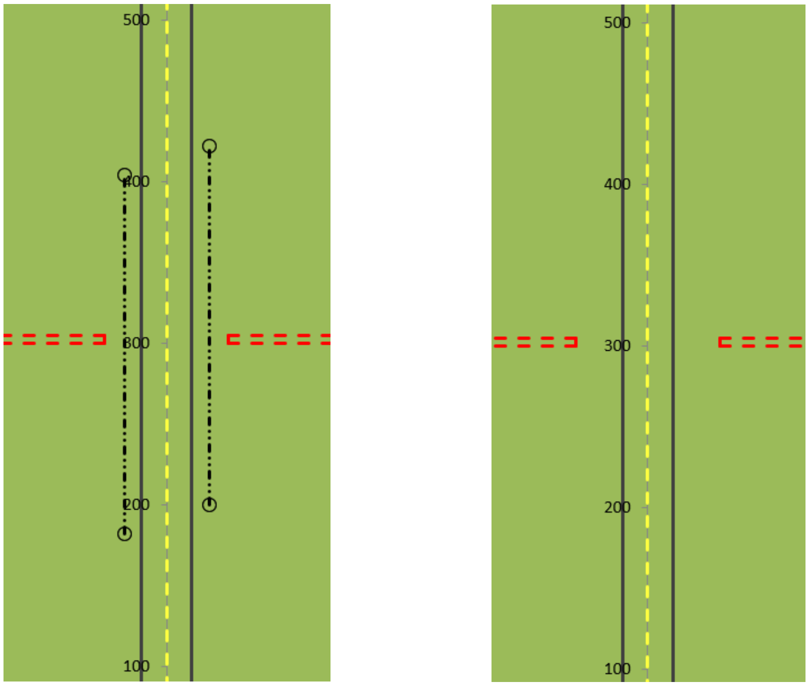
Four alternatives were defined for each scenario, namely:

a) Do nothing (base)
b) Protect the culvert using safety grates
c) Protect the culvert using steel beam guardrail
d) Extend the culvert outside the clear zone

All these alternatives are illustrated in Figure 5.3 for two-lane undivided highways, in Figure 5.4 for four-lane divided highways, and in Figure 5.5 for median culverts. For scenarios where the culvert was already outside the clear zone, only the first three alternatives were designed. In each alternative, the culvert was assumed to be perpendicular to the roadway.



Do Nothing **Safety grates installed**

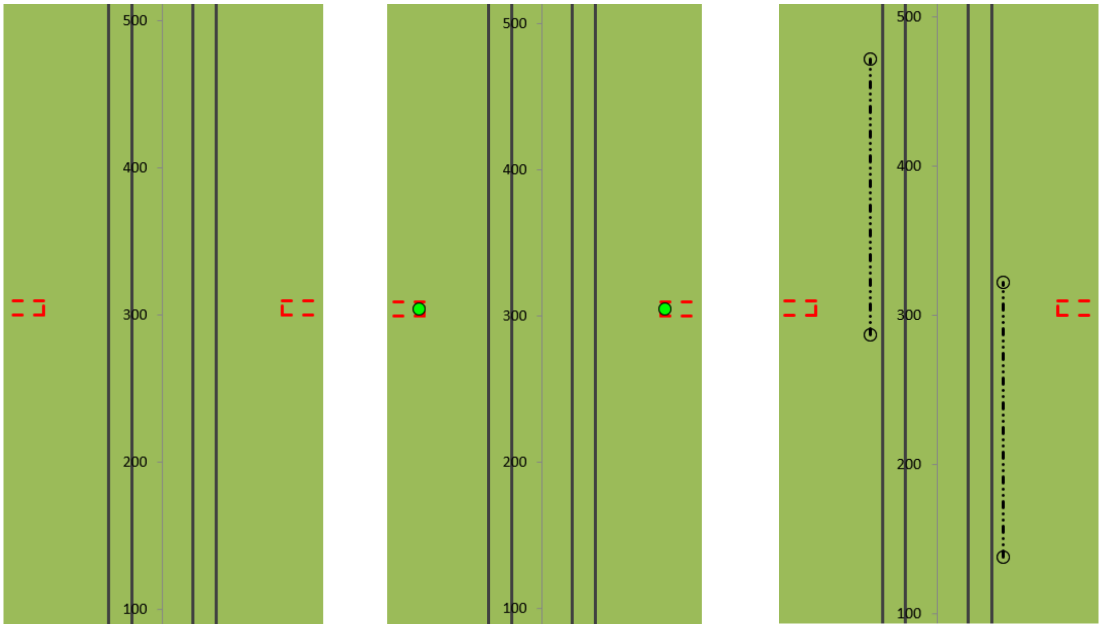


Guardrail installed **Culvert Extension**

Figure 5.3 RSAP alternatives for medium pipe culvert on two-lane 55 mph undivided highway

5.2.3.1 Do nothing

The do-nothing approach did not include any safety measures to be applied to treat the culvert. Therefore, it did not have any construction or installation costs associated with it. However, there was an annual maintenance cost of $600 for operation and maintenance of the culvert (Christiansen et al., 2014; Long, 2009). This approach was selected only if none of the other approaches provided more benefits than this alternative.



Do Nothing **Safety grates installed** **Guardrail installed**

Figure 5.4 RSAP alternatives for large box culvert on four-lane 65 mph divided highways

5.2.3.2 Protect the culvert using safety grates

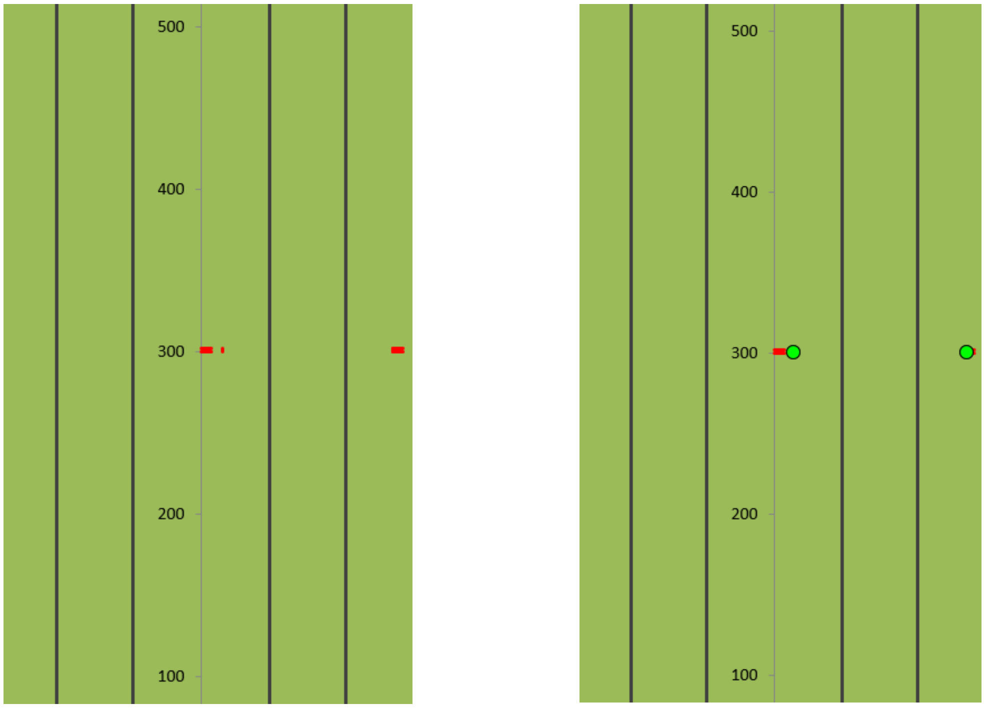
The first alternative to protect a culvert was using safety grates. The construction cost of safety grates varied with the size of culvert from $500 to $6,000. An annual maintenance cost of $200 was determined, assuming the grates are cleaned and debris is removed from the grates twice a year (United States Department of Agriculture (USDA), 2011). Since RSAP does not have any element to represent a grate, a generic fixed object of diameter equal to the width of culvert was provided at the mid-width of culvert.

5.2.3.3 Protect the culvert using steel beam guardrail

This alternative required long lengths of guardrails to be installed next to the travel lanes to protect the culvert. The guardrail length of need was calculated using a macro-enabled excel sheet provided by FHWA (FHWA, 2018). The construction cost for this treatment included the cost of the guardrail, as well as the end terminal and end anchor costs, wherever required. An annual maintenance cost of $1,000 was determined from the data provided by the Iowa DOT.

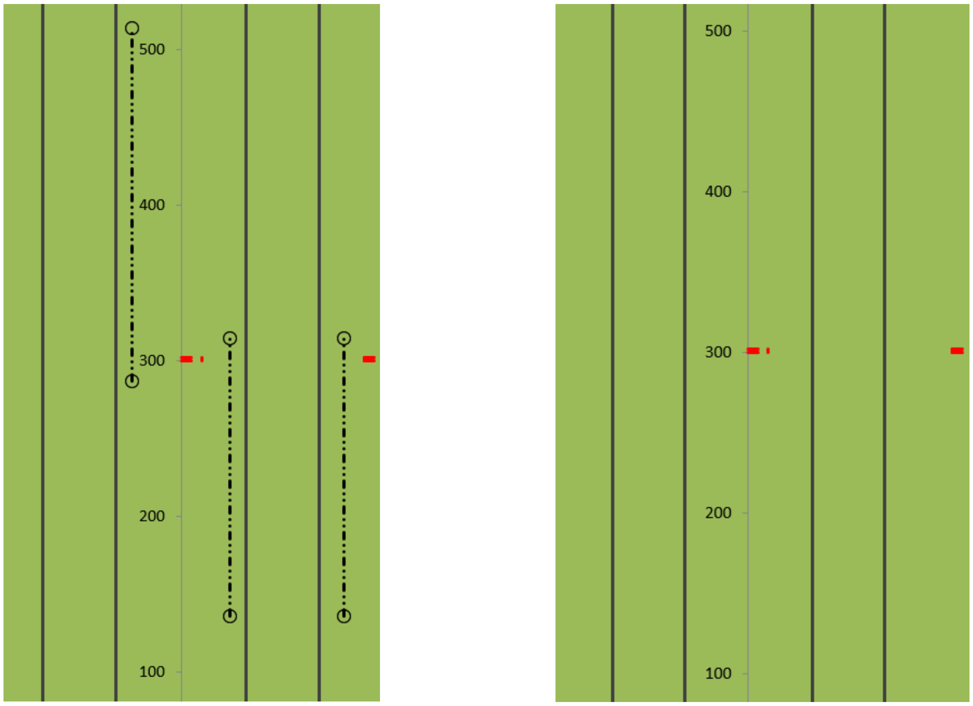
5.2.3.4 Extend the culvert outside the clear zone

The last alternative was to extend the culvert outside the clear zone. This required putting in a new culvert in place of the existing culvert with length equal to twice the distance between center of the roadway and clear zone. An annual maintenance cost of $600 was identified for the operation and maintenance of culvert from previous studies (Christiansen et al., 2014; Long, 2009).



Do Nothing

Safety grates installed



Guardrail installed

Culvert Extension

Figure 5.5 RSAP alternatives for a small pipe median culvert on six-lane 70 mph divided highways

5.2.4 Costs

5.2.4.1 Installation costs

The Iowa DOT provided the installation costs for different culverts, guardrails and safety grates. The list consisted of item number, description, and a low, high and average cost price for the items. Pipe culvert sizes ranged from 18–90 inches while box culvert sized ranged from 4–14 feet. Since this study was limited to cross-drainage culverts, entrance pipe culverts, corrugated pipe culverts, and unclassified pipe culverts were not taken into consideration. The culvert materials used to estimate costs were 3000D concrete roadway pipe, 3750D concrete roadway pipe, low clearance concrete roadway pipe, and pre-cast concrete box culverts. The end section costs were also provided for box culverts. These culverts were divided into four different categories as defined in the previous section and the average and median costs per linear foot associated with these categories were calculated, as shown in Table 5.2. There were a few cases where these costs were unusually high, and these outliers produced unrepresentative average values. Therefore, median installation costs were used for modeling in RSAP.

Table 5.2 Culvert installation costs provided by the Iowa DOT

	Average Installation Cost		**Median Installation Cost**	
Culvert Type	**Culvert Cost (LF)**	**End Sections cost (each)**	**Culvert Cost (LF)**	**End Sections cost (each)**
Small Pipe Culverts	$113.47	-	$101.43	-
Medium Pipe Culverts	$364.45	-	$311.63	-
Medium Box Culverts	$738.53	$10,889.86	$651.55	$9,592.33
Large Box Culverts	$967.44	$18,905.87	$902.25	$16,987.97

The Iowa DOT also provided costs for guardrail (Table 5.3) and safety grates (Table 5.4). As can be seen in Table 5.4 and Figure 5.6, four different types of grates are used by the Iowa DOT for protecting roadside culverts. Note that the grate bars in each of these configurations are designed to be perpendicular to the direction of traffic flow.

Table 5.3 Guardrail installation costs provided by the Iowa DOT

Guardrail Type	**Installation Cost**		
	Guardrail (LF)	**End anchor (each)**	**Tangent end terminal (each)**
Steel Beam Guardrail	$21.97	$1,259.44	$2,358.48

Table 5.4 Safety grates installation costs provided by the Iowa DOT

Safety Grate Type	**Installation Cost (each)**
Type 1	$4,381.05
Type 2	$5,081.64
Type 3	$6,656.44
Type 4	$12,227.00
Average cost	**$7,086.53**
Median cost	**$5,869.04**

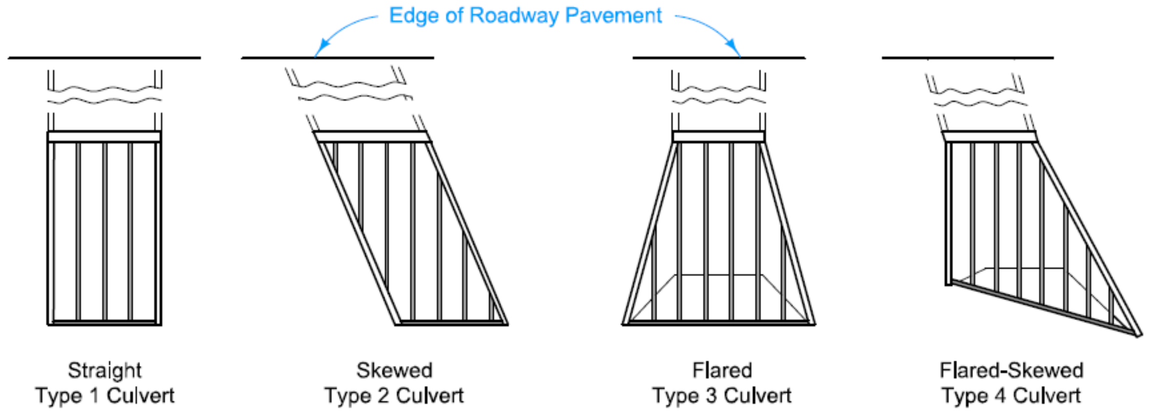


Figure 5.6 Configurations for different types of safety grates

The data provided by Iowa DOT did not include information about cost relative to the sizes of the safety grates. Online sources were consulted to obtain these costs (Haala Industries, 2018). Table 5.5 shows the safety grate costs for different sizes of culverts that were used in RSAP.

Table 5.5 Safety grate costs used in RSAP analysis

Culvert type	**Cost of safety grate (each)**
Small pipe culvert	$500
Medium pipe culvert	$2,000
Medium box culvert	$2,000
Large box culvert	$5,870

5.2.4.2 Repair Costs

The Iowa DOT provided data on culvert repair, including the item number, description of culvert, repair date, project number, quantity, unit price, location, and the total cost of the repair. As explained in the installation costs section, these costs were divided into four categories based on the size and shape, and the average and median costs per linear foot were calculated. Repair costs were not available for guardrail and safety grates. Median costs were used to model culverts in RSAP. Table 5.6 highlights the average and median repair costs provided by Iowa DOT with varying culvert types and sizes.

Table 5.6 Culvert repair costs provided by the Iowa DOT

	Average Repair Cost		**Median Repair Cost**	
Culvert Type	**Culvert Cost (LF)**	**End Sections cost (each)**	**Culvert Cost (LF)**	**End Sections cost (each)**
Small Pipe Culverts	$116.53	-	$95.25	-
Medium Pipe Culverts	$295.52	-	$236.56	-
Medium Box Culverts	$683.78	$11,045.27	$644.50	$10,664.00
Large Box Culverts	$982.16	$18,744.09	$910.00	$17,750.00

CHAPTER 6. RESULTS AND DISCUSSION

This chapter presents the results from both the crash rate analyses, as well as the scenarios that were evaluated using RSAP. Collectively, these analyses provide a quantitative basis to assess the in-service performance of existing culverts. The results of these analyses provide a framework to evaluate potential measures to improve roadside design and safety and, ultimately, to minimize the associated life-cycle costs. In addition, an example application is demonstrated and explained at the end of this chapter to familiarize the reader with RSAP.

6.1 Culvert-Involved Crash Rates by Roadway Type

A crash rate analysis was performed for different highway systems using Equation (5). Table 6.1 highlights the results for the three different highway systems that fall under the primary road network, i.e., Interstate, US Highway System and State Highway System. As mentioned earlier, the sum of average AADT was used to calculate the crash rate for a period of 10.6 years, keeping in mind that the segments associated with only perpendicular culverts were considered for the analysis of crash rates. Additionally, the crash rate analysis was performed using 500 culvert-related crashes, which excluded the missing lengths and culvert sizes.

The crash rate of the entire primary road network is 0.1512 crashes per 100 million crossing vehicles (HMCV). The lowest crash rate is for the Interstate system (0.0686 per HMCV) whereas the highest crash rate is for the State Highway System (0.2986 per HMCV). This can be attributed to the fact that Interstates have higher design standards than other facilities, with larger lane and shoulder widths, larger clear zone distances, and smoother vertical and horizontal alignments. Although the highest crash rate is for the State Highway system, the US Highway System was found to have highest total number of crashes among the other highway types.

Table 6.1 Crash rates for different highway system

System	Number of Crashes	Crash rate (per HMCV)
Interstate	134	0.0686
US Highway System	192	0.2494
State Highway System	174	0.2986
Total	**500**	**0.1512**

The crash rates were also calculated for the five different scenarios as shown in Table 6.2. The highest number of crashes were observed on two-lane 55 mph undivided highways, which also have the highest crash rate (0.4331 per HMCV). Around two-thirds of road segments in this group belong to the State Highway system, hence contributing to that high value of that system seen in Table 6.1.

Table 6.2 Crash rates for different scenarios

System	Number of Crashes	Crash rate (per HMCV)
Two-lane 55 mph undivided highways	192	0.4331
Four-lane 55 mph divided highways	31	0.1283
Four-lane 65 mph divided highways	61	0.1079
Four-lane 70 mph divided highways	82	0.0655
Six-lane 70 mph divided highways	3	0.0442

The lowest number of crashes as well as crash rate was seen on six-lane 70 mph divided highways (0.0442 per HMCV). The crash rate for four-lane 70 mph divided highways is 0.0655, which is very similar to six-lane divided highways. The total number of crashes is higher, most likely because there are relatively few six-lane segments in Iowa. The low crash rates for four-lane and six-lane divided highways is likely because their AADTs are high and they have higher design standards, since all 70 mph segments are part of the Interstate system.

To get a better understanding of how these actual crash rates relate to predicted crash rates from RSAP, a comparison needs to be done between the number of crashes and crash rates. These comparisons are highlighted in the next section within each scenario.

6.2 Roadside Safety Analysis Program (RSAP) Evaluation

Based on the different scenarios that were described in the previous sections, nineteen different RSAP models were created. Each of these models were run for three different values of statistical lives (VSL). The benefit/cost ratio increased as the VSL increased, as would be expected since VSL scales the benefit by increasing the value of the direct costs. In some cases, the culvert offsets were large, implying that the culverts were already outside the clear zone. A culvert extension alternative was not defined for such cases. The cost effectiveness analysis is presented in the following sections. Additional details are provided in Appendices A to E.

6.2.1 RSAP Scenario 1: Two-lane 55 mph undivided highways

Table 6.3 shows the RSAP results for two-lane 55 mph undivided highways. All the culverts in this scenario were crossing culverts since these were undivided highways. The culvert extension alternative was modeled only for medium pipe culverts, as this was the only case where the culvert was inside the clear zone.

In case of two-lane 55 mph undivided highways, the installation of safety grates proved to be the most favorable alternative for a majority of scenarios analyzed, except for large box culverts. None of the safety treatments were favored on an economic basis for large box culverts for VSL of $5.4 million and $6.2 million. Since the cost of installing safety grates for large box culverts is high, it results in a lower B/C ratio for this approach.

The benefit/cost ratio for large box culverts for VSL of $5.4 million and $6.2 million was greater than one for safety grates installed approach (1.31 and 1.50 respectively) but it was smaller than the decision benefit/cost ratio of two, therefore no safety treatment was justified for installation. Based on the requirements and individual judgement, the installation of safety grates can still be warranted as the best alternative for these cases.

The benefit/cost ratios for installing guardrails was seen to be negative in all cases, in general, indicating that the crash costs associated with the guardrails were always higher than the other alternatives. The B/C ratio for culvert extensions was seen to be positive in some cases; however, it was always smaller than the B/C ratio for installation of safety grates.

Table 6.3 Best case alternatives for two-lane 55 mph undivided highways

Culvert size classification	**VSL $5.4 million**			
	Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
Small pipe culverts		✓		
Medium pipe culverts		✓		
Medium box culverts		✓		
Large box culverts	✓			
	VSL $6.2 million			
	Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
Small pipe culverts		✓		
Medium pipe culverts		✓		
Medium box culverts		✓		
Large box culverts	✓			
	VSL $13.4 million			
	Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
Small pipe culverts		✓		
Medium pipe culverts		✓		
Medium box culverts		✓		
Large box culverts		✓		

After getting the number of annual crashes from RSAP simulations, the crash rate was determined in terms of HMCV. Table 6.4 highlights the number of culverts in each category, estimated and actual number of crashes for the analysis period on that system and estimated and actual crash rates. Since RSAP results represent one individual culvert, the estimated number of crashes were calculated using the estimated annual crashes and multiplying it by the number of culverts in that category and the number of years used in the analysis.

As shown in Table 6.4, RSAP predicts 0.0499 crashes per year per culvert for small pipe culverts, which implies that it predicts around 0.5 crashes per culvert for the analysis period of 10.6 years. In other words, RSAP is estimating 1 crash for every 2 culverts, which is very high. In reality, we observe 74 crashes related to 2,334 small pipe culverts. Similarly, RSAP is estimating around 0.35 crashes per culvert over 10.6 years for large box culverts or around 1 crash for every 3 culverts whereas the actual observations show 27 crashes related to 401 culverts. In general, RSAP is predicting significantly higher crashes than actual observed values on two-lane 55 mph undivided highways.

Table 6.4 Comparison of predicted and actual crash rates using estimated crashes for two-lane 55 mph undivided highways

Culvert size	**No. of culverts**	**Est. crashes per year per culvert**	**Average AADT**	**Crashes (in 10.6 years)**		**Crash rate (per HMCV)**	
				Est.	**Actual**	**Est.**	**Actual**
Small pipe	2,334	0.0499	2,828	1,234.5	74	4.8342	0.3657
Medium pipe	361	0.0642	3,114	245.7	9	5.6484	0.2493
Medium box	1,126	0.0504	2,727	601.6	50	5.0635	0.5578
Large box	401	0.0333	2,815	141.5	27	3.2410	0.7909

6.2.2 RSAP Scenario 2: Four-lane 55 mph divided highways

Table 6.5 shows the RSAP results for four-lane 55 mph divided highways. Since these were divided highways, the culverts were divided into crossing culverts and median/ramp culverts. In case of median/ramp culverts, only small pipe culverts were designed in RSAP as this was the only category in median culverts that was collected from the existing culvert database. As mentioned earlier, the culvert extension alternative was defined only for cases where the culverts were inside the clear zone; in this case, none of the culverts modeled in RSAP were inside the clear zone. Therefore, culvert extension alternative was not defined for any scenario.

For crossing culverts, none of the safety treatments were justified on an economic basis for small pipe and large box culverts whereas the installation of safety grates served as the most cost-effective alternative for medium pipe and medium box culverts. These results remain the same for all three values of statistical lives. In case of small pipe and large box culverts, the expected annual crash costs for the base approach and install safety grates approach were close to each other, which is why the B/C ratio was only 0.12 and 0.07 respectively for VSL of $6.2 million. It was also observed that the culvert offsets in these cases were high, which reduced the crash costs for the base approach and install safety grates approach. Therefore, none of the safety treatments were warranted in these cases.

For median/ramp culverts, the installation of safety grates was seen to be the best alternative. In general, the installation of safety grates was seen to be the most preferred alternative for median/ramp culverts for all the scenarios analyzed.

Table 6.5 Best case alternatives for four-lane 55 mph divided highways

	Culvert size classification	VSL $5.4 million			
Crossing culverts		**Do Nothing**	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts	✓			
	Medium pipe culverts		✓		
	Medium box culverts		✓		
	Large box culverts	✓			
		VSL $6.2 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts	✓			
	Medium pipe culverts		✓		
	Medium box culverts		✓		
	Large box culverts	✓			
		VSL $13.4 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts	✓			
	Medium pipe culverts		✓		
	Medium box culverts		✓		
	Large box culverts	✓			
Median/Ramp culverts	**Culvert size classification**	**VSL $5.4 million**			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				
		VSL $6.2 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				
		VSL $13.4 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				

Similar to how crash rates were calculated in the previous scenario, the estimated crashes and crash rates were calculated using estimated annual crashes from RSAP. These were then compared with the actual crashes and crash rates for individual categories and culvert sizes as shown in Table 6.6. The software predicts 0.1 crashes per culvert over a period of 10.6 years for small pipe crossing culverts or 1 crash for every 10 culverts whereas it actually observes 4 crashes on 242 culverts. In case of small pipe median culverts, RSAP predicts 0.2 crashes per culvert over 10.6 years whereas we see 21 crashes related to 463 culverts. In general, RSAP is estimating 4 to 7 times more crashes on four-lane 55 mph divided highways.

Table 6.6 Comparison of predicted and actual crash rates using estimated crashes for four-lane 55 mph divided highways

Category	**Culvert size**	**No. of culverts**	**Est. crashes per year per culvert**	**Average AADT**	**Crashes (in 10.6 years)**		**Crash rate (per HMCV)**	
					Est.	**Actual**	**Est.**	**Actual**
Crossing culverts	**Small pipe**	242	0.0096	13,366	24.6	4	0.1968	0.0698
	Medium pipe	70	0.0260	8,535	19.3	3	0.8346	0.1861
	Medium box	64	0.0211	8,285	14.3	2	0.6977	0.1056
	Large box	29	0.0167	10,494	5.1	1	0.4357	0.1524
Median culverts	**Small pipe**	463	0.0197	9,486	96.5	21	0.5680	0.1589

6.2.3 RSAP Scenario 3: Four-lane 65 mph divided highways

Table 6.7 shows the RSAP results for four-lane 65 mph divided highways. As in the previous case, the crossing and median/ramp culverts were modeled separately in RSAP. There were no medium box culverts found in the data collection in case of crossing culverts and only small pipe culverts were found in case of median/ramp culverts.

Table 6.7 Best case alternatives for four-lane 65 mph divided highways

	Culvert size classification	**VSL $5.4 million**			
Crossing culverts		**Do Nothing**	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts	✓			
	Medium box culverts				
	Large box culverts	✓			
		VSL $6.2 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts	✓			
	Medium box culverts				
	Large box culverts	✓			
		VSL $13.4 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts	✓			
	Medium box culverts				
	Large box culverts	✓			
Median/Ramp culverts	**Culvert size classification**	**VSL $5.4 million**			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				
		VSL $6.2 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				
		VSL $13.4 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				

For crossing culverts, the installation of safety grates served as the most cost-effective alternative for small pipe culverts whereas none of the safety treatments proved economical for medium pipe and large box culverts. In case of medium pipe and large box culverts, the culvert offset was seen to be high, which ultimately reduced the crash costs for the do nothing as well as the safety grates installation approach (B/C_{21} ratio = 0.03 and 0.02 respectively for VSL od \$6.2 million). Due to the same reason, the culvert extension alternative was not defined for these cases. The crash costs associated with the guardrails, on the other hand, were much higher than those of do nothing or safety grates since they are installed very close to the edge of the traveled way, thereby giving a much larger negative B/C ratio.

In case of median culverts, the installation of safety grates was seen to be the most favored alternative. The B/C ratio was seen to be 8.64 for installation of safety grates whereas this value was 2.25 for the culvert extension over the do nothing approach for a VSL of \$13.4 million.

Table 6.8 compares the predicted and actual crash rates using estimated annual crashes from RSAP. Interestingly, for medium pipe and large box crossing culverts, RSAP is seen to estimate around 0.09 crashes per culvert over 10.6 years or 4.7 crashes and 3.8 crashes related to 54 and 42 culverts respectively. In reality, we observe 8 and 6 crashes respectively during the analysis period, which is 1.6-1.7 times more crashes than what RSAP predicts. RSAP predicted lesser number of crashes than actual number of crashes in that category, due to which the actual crash rates are higher than the estimated crash rates.

Table 6.8 Comparison of predicted and actual crash rates using estimated crashes for four-lane 65 mph divided highways

Category	Culvert size	No. of culverts	Est. crashes per year per culvert	Average AADT	Crashes (in 10.6 years)		Crash rate (per HMCV)	
					Est.	Actual	Est.	Actual
Crossing culverts	**Small pipe**	234	0.0486	15,723	120.5	9	0.8469	0.0651
	Medium pipe	54	0.0082	12,135	4.7	8	0.1845	0.2547
	Medium box							
	Large box	42	0.0085	9,897	3.8	6	0.2347	0.3139
Median culverts	**Small pipe**	557	0.0380	18,390	224.4	38	0.5663	0.1274

6.2.4 RSAP Scenario 4: Four-lane 70 mph divided highways

Table 6.9 shows the RSAP results for four-lane 70 mph divided highways. Only small pipe culverts were modeled in RSAP for median/ramp culverts because these were the only culverts that were seen to be present in the culvert database. The culvert extension alternative was defined only for small pipe crossing culverts as only these culverts were seen to be inside the clear zone.

For crossing culverts, the installation of safety grates was observed to be the optimal choice except for medium box culverts, where none of the safety treatments were warranted as economical. It is interesting to note that even though the installation costs of safety grates for large box culverts is high, it still proved to be the most favored alternative. In addition to that, the main reason for none of the treatments proving economical for medium box culverts is a larger culvert offset from the center line of the roadway.

Table 6.9 Best case alternatives for four-lane 70 mph divided highways

	Culvert size classification	**VSL $5.4 million**			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
Crossing culverts	Small pipe culverts		✓		
	Medium pipe culverts		✓		
	Medium box culverts	✓			
	Large box culverts		✓		
		VSL $6.2 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts		✓		
	Medium box culverts	✓			
	Large box culverts		✓		
		VSL $13.4 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts		✓		
	Medium box culverts	✓			
	Large box culverts		✓		
Median/Ramp culverts	**Culvert size classification**	**VSL $5.4 million**			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				
		VSL $6.2 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				
		VSL $13.4 million			
		Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
	Small pipe culverts		✓		
	Medium pipe culverts				
	Medium box culverts				
	Large box culverts				

In case of median/ramp culverts, the safety grates proved to be the optimal choice for all three values of statistical lives, as is the case with the other scenarios. The B/C ratio was seen to be 8.79 for installation of safety grates whereas this value was 1.77 for the culvert extension over the base (do nothing) approach for a VSL of $13.4 million. However, the B/C ratio for installation of guardrails over do-nothing approach came out to be -20.39, showing how highly ineffective the guardrail installation will be if it were to install on such roadways.

In a similar fashion as shown above, the estimated crashes and crash rates were calculated using estimated annual crashes from RSAP. These were then compared with the actual crashes and crash rates for individual categories and culvert sizes as shown in Table 6.10. It was observed that RSAP predicted around 3 to 9 times more crashes on four-lane 70 mph divided highways.

Table 6.10 Comparison of predicted and actual crash rates using estimated crashes for four-lane 70 mph divided highways

Category	**Culvert size**	**No. of culverts**	**Est. crashes per year per culvert**	**Average AADT**	**Crashes (in 10.6 years)**		**Crash rate (per HMCV)**	
					Est.	**Actual**	**Est.**	**Actual**
Crossing culverts	**Small pipe**	461	0.0509	23,266	248.7	26	0.5994	0.0656
	Medium pipe	48	0.0380	27,781	19.3	6	0.3746	0.1442
	Medium box	130	0.0176	27,809	24.3	8	0.1735	0.0656
	Large box	55	0.0409	35,845	23.8	4	0.3123	0.0780
Median culverts	**Small pipe**	663	0.0299	29,528	210.3	37	0.2776	0.0645

6.2.5 RSAP Scenario 5: Six-lane 70 mph divided highways

Table 6.11 shows the RSAP results for six-lane 70 mph divided highways. Crashes were seen to occur only with the small median/ramp pipe culverts, therefore, only these culverts were modeled in RSAP. The safety grates installation was seen to be the most favored alternative as compared to the other options with a B/C ratio of 4.78 for a VSL of \$6.2 million. The B/C ratio for culvert extension alternative was seen to be 1.96, which is very close to the decision point B/C ratio. Again, the guardrail installation alternative was seen to be associated with high negative B/C ratios.

Interestingly, the expected annual crash costs associated with installation of safety grates and culvert extensions was seen to be very close, which resulted in a benefit-cost ratio close to zero (B/C ratio = 0.07) for VSL of \$6.2 million. The highest B/C ratio observed among all the scenarios defined above was seen to be for these culverts for a VSL of \$13.4 million (B/C_{21} ratio = 10.34).

Table 6.11 Best case alternatives for six-lane 70 mph divided highways

Culvert size classification	**VSL \$5.4 million**			
	Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
Small pipe culverts		✓		
Medium pipe culverts	■	■	■	■
Medium box culverts	■	■	■	■
Large box culverts	■	■	■	■
	VSL \$6.2 million			
	Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
Small pipe culverts		✓		
Medium pipe culverts	■	■	■	■
Medium box culverts	■	■	■	■
Large box culverts	■	■	■	■
	VSL \$13.4 million			
	Do Nothing	**Safety grates installed**	**Guardrail installed**	**Culvert extension**
Small pipe culverts		✓		
Medium pipe culverts	■	■	■	■
Medium box culverts	■	■	■	■
Large box culverts	■	■	■	■

Table 6.12 shows the estimated and actual number of crashes and crash rates as calculated from estimated annual crashes from RSAP. The software was seen to predict around 0.5 crashes per culvert over 10.6 years or 1 crash for every 2 culverts in that category. In this case, we actually observe 3 crashes on 43 culverts for the analysis period, which implies that RSAP predicted 7 times more crashes than the actual values.

Table 6.12 Comparison of predicted and actual crash rates using estimated crashes for six-lane 70 mph divided highways

Culvert size	**No. of culverts**	**Est. crashes per year per culvert**	**Average AADT**	**Crashes (in 10.6 years)**		**Crash rate (per HMCV)**	
				Est.	**Actual**	**Est.**	**Actual**
Small median pipe	43	0.0464	23,676	21.1	3	0.5367	0.0800

6.2.6 Example Application

This section shows an example of how benefit/cost ratios were calculated using RSAP. This example highlights RSAP modeling for a medium pipe culvert on a two-lane 55 mph undivided highway for VSL of $6.2 million.

The cost of installation of safety grates, guardrail and culvert extensions for this scenario were $4000, $14,540 and $21,191. The do-nothing approach did not involve any installation costs. These were calculated based on the costs that the Iowa DOT provided. Since these were the initial investments, these were required to be converted to the annualized costs for the calculation of benefit/cost ratios. These direct costs were annualized using the equation:

$$A = P\left[\frac{i.(1+i)^n}{(1+i)^n - 1}\right] \qquad (6)$$

Where,

A = annual payment over n years

P = initial investment required (installation cost)

i = interest rate

n = project life/design life

For a rate of return of 4% and design life of 20 years, these values were converted to annualized payments. After being annualized, these costs came out to be $294, $1,070, and $1,559, respectively. The annual maintenance cost for a culvert, safety grates and guardrail were $600, $200, and $1,000, respectively. Therefore, the annual maintenance costs for these alternatives came out to be $600, $800, $1,600 and $600 respectively. The expected annual repair costs and expected annual crash costs were the results from RSAP modeling. Alternatives 1 and 4 have the same annual maintenance and repair cost as they differ only in their offsets from the center line. Table 6.13 provides the details of different costs from the Iowa DOT and RSAP results.

Table 6.13 Costs from the Iowa DOT and RSAP

Alternatives	**Annual installation cost (I)**	**Annual maintenance cost (M)**	**Expected Annual Repair Cost (R)**	**Expected Annual Crash cost (CC)**
Do nothing (Alt 1)	$0	$600	$0	$6,747
Safety grates installed (Alt 2)	$294	$800	$1	$4,993
Guardrail installed (Alt 3)	$1,070	$1,600	$132	$10,098
Culvert extension (Alt 4)	$1,559	$600	$0	$5,670

A proper detailed summary of costs, crash and injury information can help in a reliable estimation of benefit-cost analyses (Alluri, Haleem, & Gan, 2012). As mentioned earlier, the incremental benefit-cost ratio generated in RSAP is computed by calculating the reduction in crash costs (CC) and dividing by the total cost of improvement (considering installation, maintenance and repair costs) as shown in Equation (7). The indices i and j correspond to different alternatives; for example, BCR_{21} corresponds to benefit/cost ratio of Alternative 2 as compared to Alternative 1.

$$BCR_{ji} = \frac{CC_i - CC_j}{(I_j + M_j + R_j) - (I_i + M_i + R_i)} \tag{7}$$

The existing approach (do nothing) is the base case alternative. Firstly, BCR_{21} is calculated to compare the Alternative 2 with Alternative 1.

$$BCR_{21} = \frac{CC_1 - CC_2}{(I_2 + M_2 + R_2) - (I_1 + M_1 + R_1)} = \frac{6747 - 4993}{(294 + 800 + 1) - (0 + 600 + 0)}$$

$$= 3.54$$

This implies that installing safety grates will give a B/C ratio of 3.54 as compared to do nothing approach. Therefore, installing a culvert grate is cost beneficial. Now, the other alternatives will be compared to safety grates installed approach. The incremental B/C ratio for installing guardrails as compared to safety grates is calculated as:

$$BCR_{32} = \frac{CC_2 - CC_3}{(I_3 + M_3 + R_3) - (I_2 + M_2 + R_2)}$$

$$= \frac{4993 - 10098}{(1070 + 1600 + 132) - (294 + 800 + 1)} = -2.99$$

This B/C ratio is negative which implies that the crash costs associated with guardrails are higher than those for safety grates. This makes sense because guardrails are installed much closer to the edge of traveled way and therefore are more prone to striking from vehicles. Therefore, guardrail installation is not recommended. Thus, safety grate installation still remains the basis for comparison with the last alternative, culvert extension. The incremental B/C ratio for culvert extension as compared to safety grates is calculated as:

$$BCR_{42} = \frac{CC_2 - CC_4}{(I_4 + M_4 + R_4) - (I_2 + M_2 + R_2)}$$

$$= \frac{4993 - 5670}{(1559 + 600 + 0) - (294 + 800 + 1)} = -0.64$$

The B/C ratio for this alternative is also negative as compared to safety grates. Since guardrail installation and culvert extension both showed a negative B/C ratio as compared to safety grates and safety grates showed a positive B/C ratio as compared to the base approach of leaving the culvert unprotected, safety grates was justified as the most optimal alternative. Table 6.14 shows the final benefit-cost ratios matrix as calculated using RSAP.

Table 6.14 Benefit-cost ratios matrix between different alternatives

VSL $6.2 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	3.54	-1.52	0.69
Alt. 2		0.00	-2.99	-0.64
Alt. 3			0.00	-6.89
Alt. 4				0.00

CHAPTER 7. CONCLUSION

7.1 Summary of key findings

The purpose of this study was to assess potential impacts of installing various safety treatments to mitigate the frequency and severity of collisions in which an errant vehicle strikes a culvert. This included evaluations of the cost-effectiveness of these safety treatments as compared to the baseline do-nothing scenario. The project started with an in-depth evaluation of the existing culvert database provided by the Iowa DOT. The existing design practices as recommended in the AASHTO Roadside Design Guide, as well as state design practices of the Iowa DOT were reviewed. In addition, a questionnaire survey was sent out to other state DOTs to document current design practices as they relate to the use of various types of culvert safety treatments.

An extensive literature review was conducted to identify potential safety treatments for protecting roadside culverts, as well any studies documenting the efficacy of such treatments. These treatments included shielding the culvert openings with safety grates, protecting the culverts through the installation of longitudinal guardrail, or extending the culverts outside the clear zone. Each of these safety treatments and the associated installation and design issues were discussed in detail. In addition, benefit cost analysis methods were described in detail, which were subsequently used to examine the cost-effectiveness of these safety treatments.

Subsequently, the existing culvert database was filtered to isolate only cross drainage culverts. Missing data for these culverts, including critical elements such as culvert length, were reviewed and rectified to the extent possible using a review of aerial imagery. An attempt was made to identify all crashes related to culverts. This was done through a review of standard fields on the Iowa crash report form, as well as through a review of pertinent keywords from the narrative section of the forms. These crashes were then linked to the nearest cross drainage culvert, which was associated with the nearest road segment on the primary (state-maintained) road network. After removing culverts with unknown lengths or diameters, the final dataset included 500 crashes that occurred at 481 culverts between January 2007 and August 2017. A high-level analysis was performed on the occupant injury data resulting from these 500 crashes to determine how the severity distribution varied based upon the roadway type.

The first stage of the analysis involved the estimation of culvert-involved crash rates for different highway types. Crash rates were highest for the State highway system (0.2986 per HMCV), as well as on two-lane 55 mph undivided highways (0.4331 per HMCV). The lowest crash rates were observed on the Interstate system (0.0686 per HMCV), where higher design standards are in place, which include greater clear zone distances and less abrupt changes in horizontal and vertical alignment.

The second stage of the analysis involved the use of the Roadside Safety Analysis Program (RSAP), an encroachment-based software developed under NCHRP Project 22-09. This software can be used to estimate the expected crash costs associated with various highway scenarios. This information can be used as part of an incremental benefit-cost analysis to identify which safety treatments are most cost-effective under various scenarios. A series of scenarios were evaluated, culminating in guidance as to the most cost-effective treatments for different combinations of roadway geometric and traffic characteristics. Information regarding the installation and maintenance costs were obtained from the Iowa DOT and several online resources. Nineteen different models were designed in RSAP based on the highway system and culvert sizes and three different values of statistical life ($5.4 million, $6.2 million and $13.4 million) were considered as a part of a sensitivity analysis.

The number of crashes predicted using RSAP for these scenarios were extrapolated to provide an estimate that could be compared to the actual observed values from the crash data analysis. The crash rates estimated using RSAP were generally 2 to 13 times higher than the actual crash rates. There are several potential explanations for this discrepancy. First, it is expected that there are a significant number of culvert-involved crashes that go unreported, particularly for collisions with smaller culverts where vehicle damage is minimal. Secondly, the scenarios considered in RSAP were generally instances where the risks of encroachments and culvert-involved collisions were higher. As many of the existing culverts are beyond the clear zone, lower rates may be expected. The actual crash rates were only observed to be higher than the rates predicted by RSAP for the cases of medium pipe and large box culverts along four-lane divided highways with 65-mph speed limits.

Ultimately, the results of this study suggest that the installation of safety grates on culvert openings provides a promising alternative for cases where the culvert is located within the clear zone. Grates are expected to reduce the level of injury sustained by crash-involved occupants, as well as the associated crash costs, resulting in a higher benefit/cost ratio. The installation of safety grates was found to be the most economical choice for most highway types and for different culvert sizes in the analyses. This is mainly because of the large reductions in crash costs and low installation and maintenance costs as compared to other alternatives.

In the case of two-lane 55 mph undivided highways, installing safety grates was seen to be most cost-effective as compared to other alternatives for all types of culverts, except large box culverts, where none of the safety treatments were found to be economically justified. For four-lane 55 mph divided highways, installing safety grates was justified as the most favorable treatment for medium pipe and medium box crossing culverts whereas none of the safety treatments proved beneficial for small pipe and large box crossing culverts. For median/ramp culverts in any scenario, safety grates installation was seen to be the most cost-effective treatment.

In case of four-lane 65 mph divided highways, safety grates installation was cost-effective only for small pipe crossing culverts whereas the base (do-nothing) approach was warranted for medium pipe and large box culverts. For four-lane 70 mph divided highways, installing safety grates was most beneficial except for medium box culverts, where none of the safety treatments were justified on an economic basis.

In cases where extension of culverts outside the clear zone was defined, the results showed that the B/C ratio was positive; however, this was always less than the B/C ratio for the installation of safety grates. On the other hand, the installation of guardrail was associated with a higher number of crashes, though the severity of such crashes tended to be less severe than in the absence of guardrail. The B/C ratios for the installation of guardrails near the edge of the travel lanes were significantly negative, mainly because of the increase in crash costs and high installation and maintenance costs compared to the other alternatives. The magnitude of these B/C ratios was seen to increase with the increasing value of statistical life (VSL). In general, guardrail is recommended when adverse conditions are present (e.g., large drop-offs) or when other treatments are not feasible at a specific location.

7.2 Limitations and future work

There are several limitations that can be addressed through future work or to changes in the manner in which the Iowa DOT maintains its culvert inventory data. One of the main limitations of this project was the degree of missing or incomplete information in the culvert database. This required an extensive quality assurance review and some manual investigation to fill in missing data where possible. Ultimately, approximately 10 percent of the culvert sizes were missing from the analyzed data, which resulted in a limited sample for specific categories of culverts.

Another limitation of this study is due to the fact that the crash information provided for this study was based upon information in police crash reports. There may have been cases where a crash occurred with a culvert but it was not reported. A review conducted by Wood et al. (2016) showed that between 11 and 65 percent of crashes go unreported. RSAP predicts crashes based on the encroachment and vehicle trajectory data and, as such, may be expected to provide a more accurate estimate of the number of culvert-involved crashes. This is one reason for the differences observed between the predicted and actual number of crashes. Generally, these unreported crashes tend to be less severe.

The installation costs provided by the Iowa DOT for safety grates was a general figure that was not associated with a specific size of grate. The costs for different sizes of safety grates was found from an online source. The maintenance costs for culverts and safety grates were found through literature review; however, these costs did not have a size associated with them either. Therefore, the same maintenance costs were used for all culverts and all safety grates irrespective of their sizes.

Another limitation is related to the RSAP software and the underlying data upon which the program is based. The run-off-road crash frequencies generated by RSAPv3 are based on the encroachment data collected by Cooper (1980). These data were collected in the 1970s in Canada and there are some ranges of volume and geometric conditions in which data are sparse. An ongoing NCHRP study (NCHRP 17-88) is aimed at updating these data, which may provide improved predictive capabilities.

In the analyses performed in this study, it was assumed that the maintenance costs for culverts, safety grates and guardrails remained the same for varying lengths and sizes. With a better dataset having the accurate installation and maintenance costs with varying sizes for culverts and safety grates, it will be interesting to see how these results vary. Currently, the culverts were combined into groups based on highway classification, speed limit, number of lanes, median type and culvert sizes. As a future research work, each culvert from the list of those 547 culverts can be modeled separately in RSAP. This way the simulations will give accurate results and safety treatments can be chosen thereafter based on the individual results.

In the data collection part, the distance to nearest culvert was chosen as 500 m keeping in mind the conditions where the vehicle would have struck the culvert and still continued to travel up to some distance before coming to a stop. In case of such crashes, it will be better to know the exact location of the culvert so as to trace the right culvert for safety evaluation.

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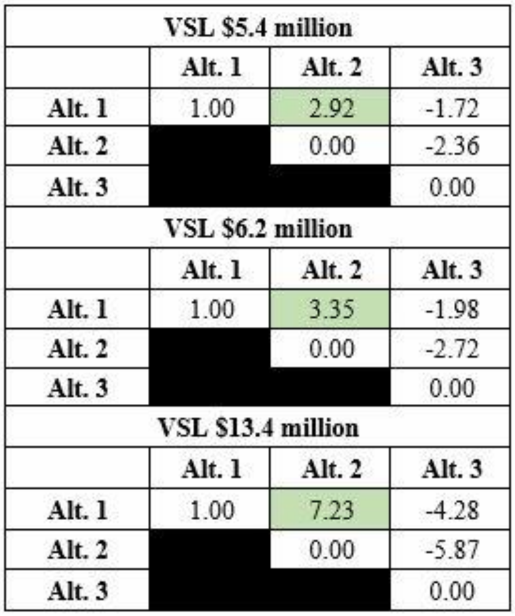
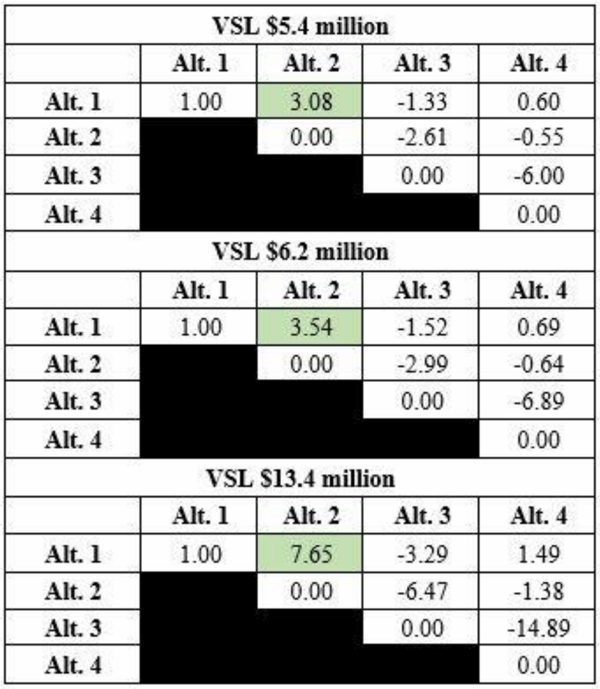
APPENDIX A – BENEFIT- COST RATIOS MATRIX FOR TWO-LANE 55 MPH UNDIVIDED HIGHWAYS

Table A-1 B/C ratios for small pipe culverts



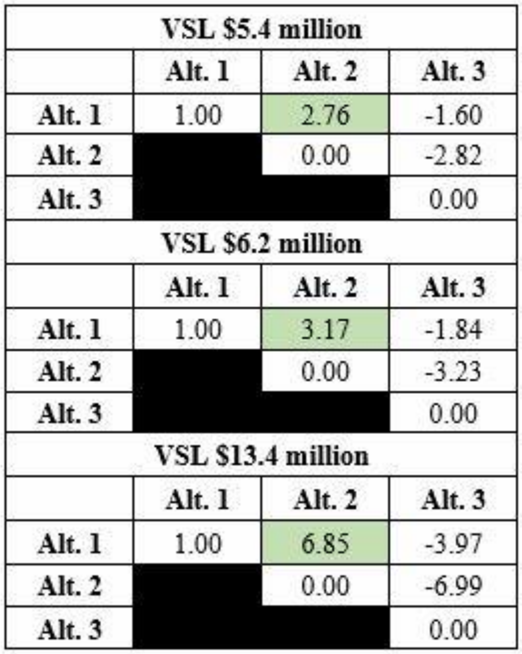
VSL $5.4 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	2.92	-1.72
Alt. 2		0.00	-2.36
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	3.35	-1.98
Alt. 2		0.00	-2.72
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	7.23	-4.28
Alt. 2		0.00	-5.87
Alt. 3			0.00

Table A-2 B/C ratios for medium pipe culverts



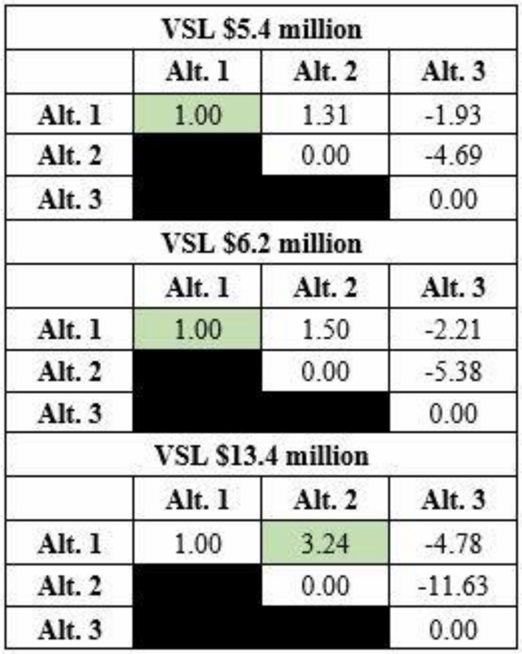
VSL $5.4 million				
	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Alt. 1	1.00	3.08	-1.33	0.60
Alt. 2		0.00	-2.61	-0.55
Alt. 3			0.00	-6.00
Alt. 4				0.00
VSL $6.2 million				
	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Alt. 1	1.00	3.54	-1.52	0.69
Alt. 2		0.00	-2.99	-0.64
Alt. 3			0.00	-6.89
Alt. 4				0.00
VSL $13.4 million				
	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Alt. 1	1.00	7.65	-3.29	1.49
Alt. 2		0.00	-6.47	-1.38
Alt. 3			0.00	-14.89
Alt. 4				0.00

Table A-3 B/C ratios for medium box culverts



VSL $5.4 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	2.76	-1.60
Alt. 2		0.00	-2.82
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	3.17	-1.84
Alt. 2		0.00	-3.23
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	6.85	-3.97
Alt. 2		0.00	-6.99
Alt. 3			0.00

Table A-4 B/C ratios for large box culverts



VSL $5.4 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	1.31	-1.93
Alt. 2		0.00	-4.69
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	1.50	-2.21
Alt. 2		0.00	-5.38
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	Alt. 2	Alt. 3
Alt. 1	1.00	3.24	-4.78
Alt. 2		0.00	-11.63
Alt. 3			0.00

APPENDIX B – BENEFIT- COST RATIOS MATRIX FOR FOUR-LANE 55 MPH DIVIDED HIGHWAYS

Table B-1 B/C ratios for small pipe crossing culverts

VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.10	-2.53
Alt. 2		0.00	-2.98
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.12	-2.91
Alt. 2		0.00	-3.42
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.26	-6.28
Alt. 2		0.00	-7.39
Alt. 3			0.00

Table B-2 B/C ratios for medium pipe crossing culverts

VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	2.11	-2.07
Alt. 2		0.00	-3.70
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	2.43	-2.38
Alt. 2		0.00	-4.25
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	5.24	-5.14
Alt. 2		0.00	-9.19
Alt. 3			0.00

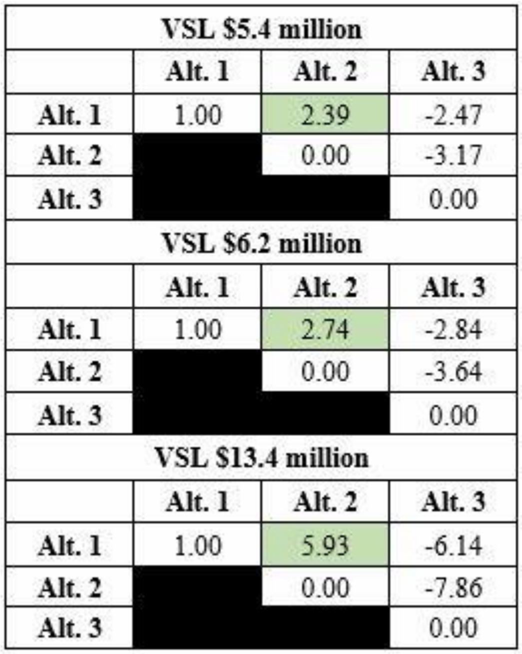
Table B-3 B/C ratios for medium box crossing culverts

VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	4.01	-2.13
Alt. 2		0.00	-4.53
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	4.60	-2.44
Alt. 2		0.00	-5.20
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	9.94	-5.27
Alt. 2		0.00	-11.25
Alt. 3			0.00

Table B-4 B/C ratios for large box crossing culverts

VSL $5.4 million			
	Alt. 1	**Alt. 3**	**Alt. 2**
Alt. 1	1.00	-3.44	0.07
Alt. 3		0.00	-8.43
Alt. 2			0.00
VSL $6.2 million			
	Alt. 1	**Alt. 3**	**Alt. 2**
Alt. 1	1.00	-3.95	0.07
Alt. 3		0.00	-9.68
Alt. 2			0.00
VSL $13.4 million			
	Alt. 1	**Alt. 3**	**Alt. 2**
Alt. 1	1.00	-8.55	0.16
Alt. 3		0.00	-20.92
Alt. 2			0.00

Table B-5 B/C ratios for small pipe median/ramp culverts



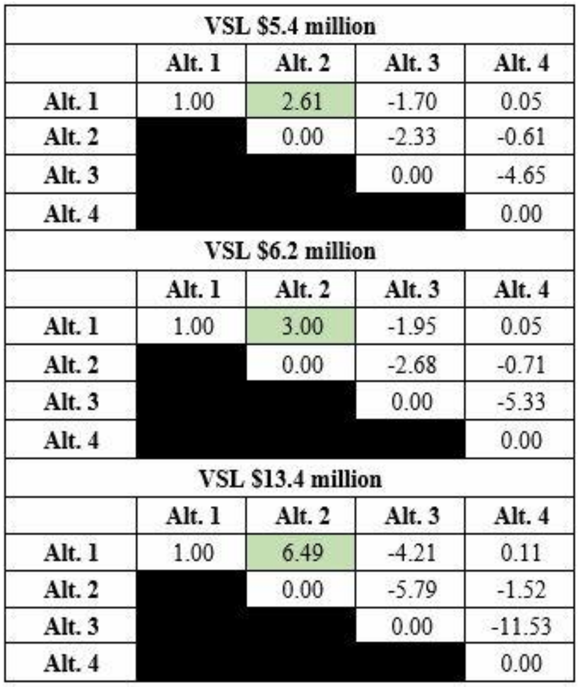
VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	2.39	-2.47
Alt. 2		0.00	-3.17
Alt. 3			0.00

VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	2.74	-2.84
Alt. 2		0.00	-3.64
Alt. 3			0.00

VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	5.93	-6.14
Alt. 2		0.00	-7.86
Alt. 3			0.00

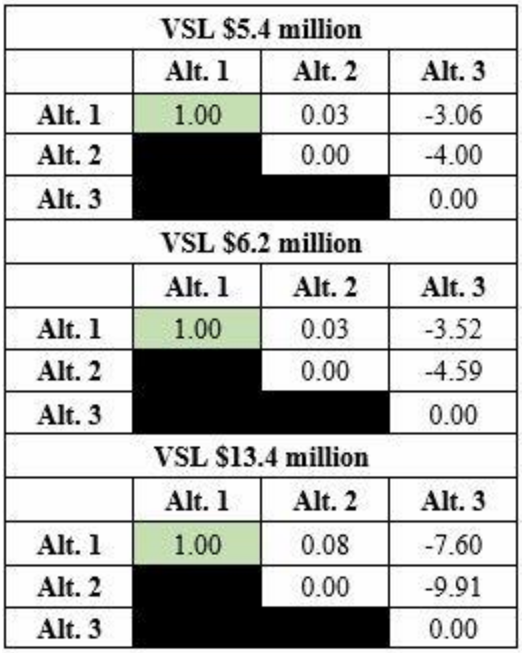
APPENDIX C – BENEFIT- COST RATIOS MATRIX FOR FOUR-LANE 65 MPH DIVIDED HIGHWAYS

Table C-1 B/C ratios for small pipe crossing culverts



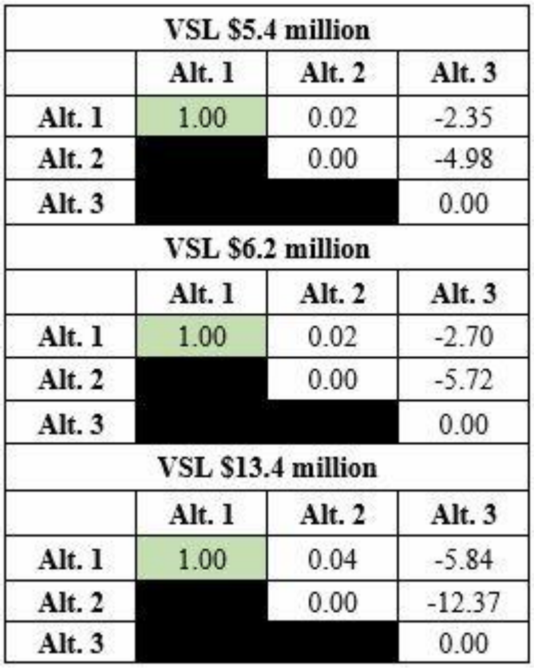
VSL $5.4 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	2.61	-1.70	0.05
Alt. 2		0.00	-2.33	-0.61
Alt. 3			0.00	-4.65
Alt. 4				0.00
VSL $6.2 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	3.00	-1.95	0.05
Alt. 2		0.00	-2.68	-0.71
Alt. 3			0.00	-5.33
Alt. 4				0.00
VSL $13.4 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	6.49	-4.21	0.11
Alt. 2		0.00	-5.79	-1.52
Alt. 3			0.00	-11.53
Alt. 4				0.00

Table C-2 B/C ratios for medium pipe crossing culverts



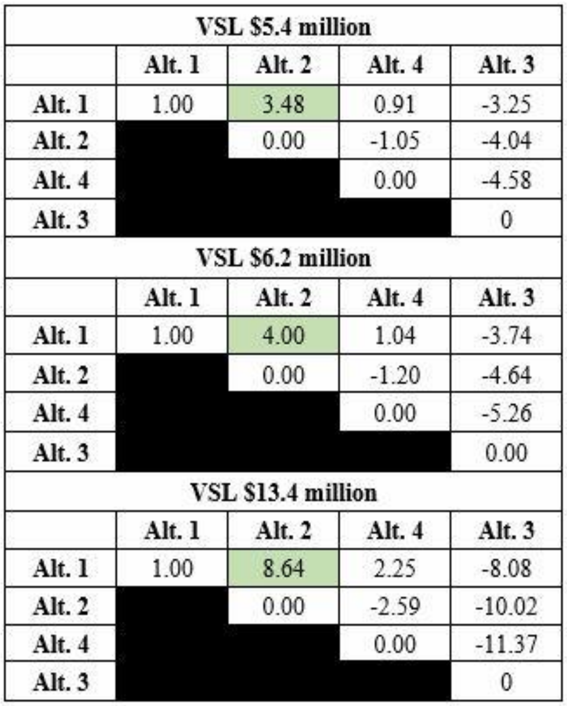
VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.03	-3.06
Alt. 2		0.00	-4.00
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.03	-3.52
Alt. 2		0.00	-4.59
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.08	-7.60
Alt. 2		0.00	-9.91
Alt. 3			0.00

Table C-3 B/C ratios for medium box crossing culverts



VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.02	-2.35
Alt. 2		0.00	-4.98
Alt. 3			0.00
VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.02	-2.70
Alt. 2		0.00	-5.72
Alt. 3			0.00
VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.04	-5.84
Alt. 2		0.00	-12.37
Alt. 3			0.00

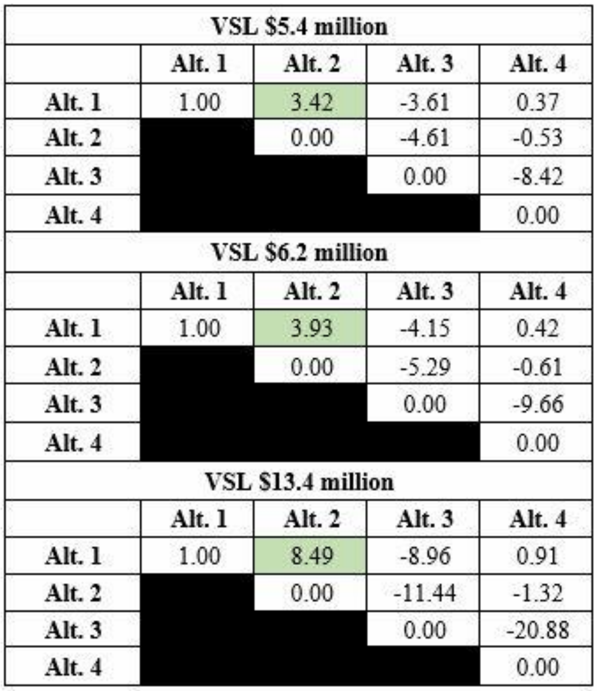
Table C-4 B/C ratios for large box crossing culverts



VSL $5.4 million				
	Alt. 1	**Alt. 2**	**Alt. 4**	**Alt. 3**
Alt. 1	1.00	3.48	0.91	-3.25
Alt. 2		0.00	-1.05	-4.04
Alt. 4			0.00	-4.58
Alt. 3				0
VSL $6.2 million				
	Alt. 1	**Alt. 2**	**Alt. 4**	**Alt. 3**
Alt. 1	1.00	4.00	1.04	-3.74
Alt. 2		0.00	-1.20	-4.64
Alt. 4			0.00	-5.26
Alt. 3				0.00
VSL $13.4 million				
	Alt. 1	**Alt. 2**	**Alt. 4**	**Alt. 3**
Alt. 1	1.00	8.64	2.25	-8.08
Alt. 2		0.00	-2.59	-10.02
Alt. 4			0.00	-11.37
Alt. 3				0

APPENDIX D – BENEFIT- COST RATIOS MATRIX FOR FOUR-LANE 70 MPH DIVIDED HIGHWAYS

Table D-1 B/C ratios for small pipe crossing culverts

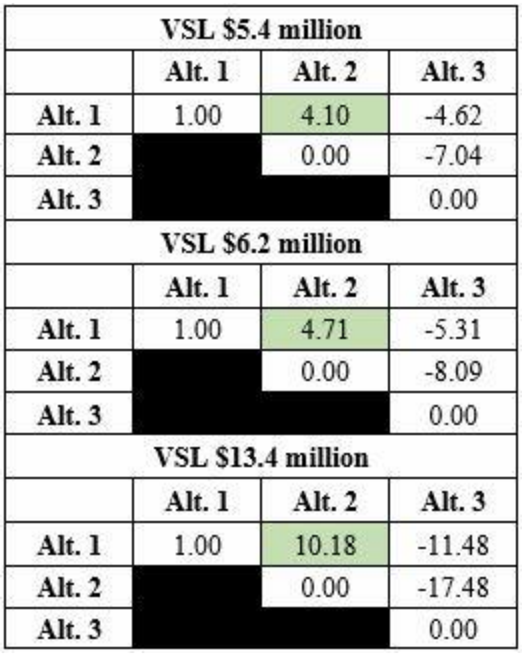


VSL $5.4 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	3.42	-3.61	0.37
Alt. 2		0.00	-4.61	-0.53
Alt. 3			0.00	-8.42
Alt. 4				0.00

VSL $6.2 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	3.93	-4.15	0.42
Alt. 2		0.00	-5.29	-0.61
Alt. 3			0.00	-9.66
Alt. 4				0.00

VSL $13.4 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	8.49	-8.96	0.91
Alt. 2		0.00	-11.44	-1.32
Alt. 3			0.00	-20.88
Alt. 4				0.00

Table D-2 B/C ratios for medium pipe crossing culverts

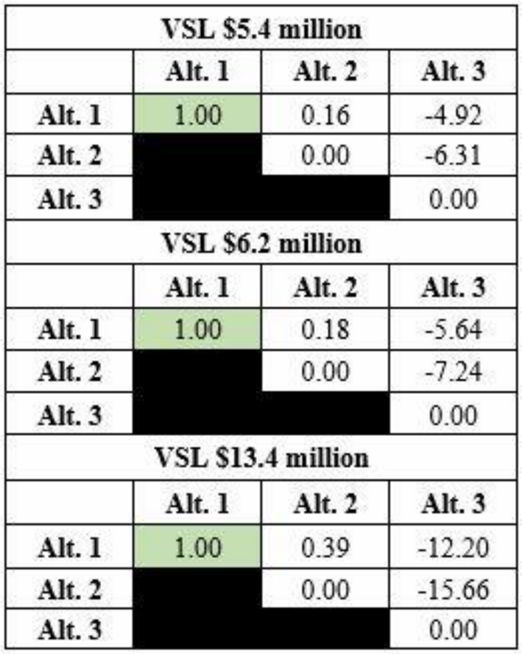


VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	4.10	-4.62
Alt. 2		0.00	-7.04
Alt. 3			0.00

VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	4.71	-5.31
Alt. 2		0.00	-8.09
Alt. 3			0.00

VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	10.18	-11.48
Alt. 2		0.00	-17.48
Alt. 3			0.00

Table D-3 B/C ratios for medium box crossing culverts

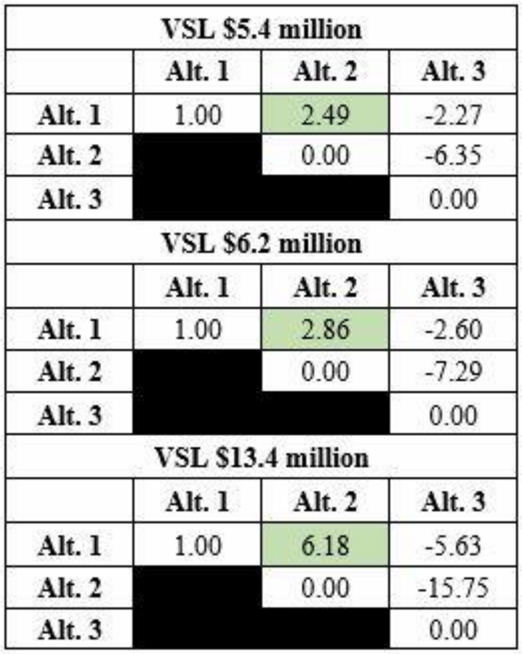


VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.16	-4.92
Alt. 2		0.00	-6.31
Alt. 3			0.00

VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.18	-5.64
Alt. 2		0.00	-7.24
Alt. 3			0.00

VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	0.39	-12.20
Alt. 2		0.00	-15.66
Alt. 3			0.00

Table D-4 B/C ratios for large box crossing culverts

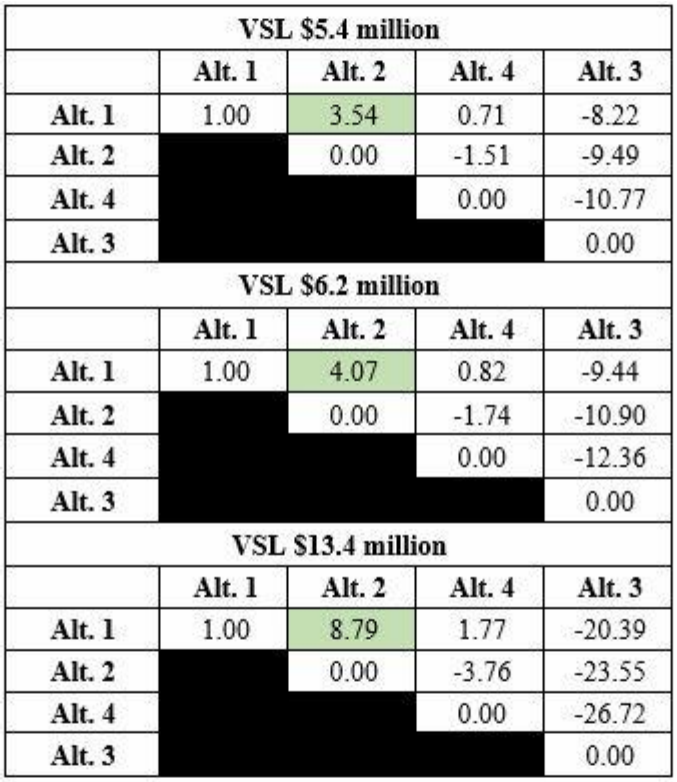


VSL $5.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	2.49	-2.27
Alt. 2		0.00	-6.35
Alt. 3			0.00

VSL $6.2 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	2.86	-2.60
Alt. 2		0.00	-7.29
Alt. 3			0.00

VSL $13.4 million			
	Alt. 1	**Alt. 2**	**Alt. 3**
Alt. 1	1.00	6.18	-5.63
Alt. 2		0.00	-15.75
Alt. 3			0.00

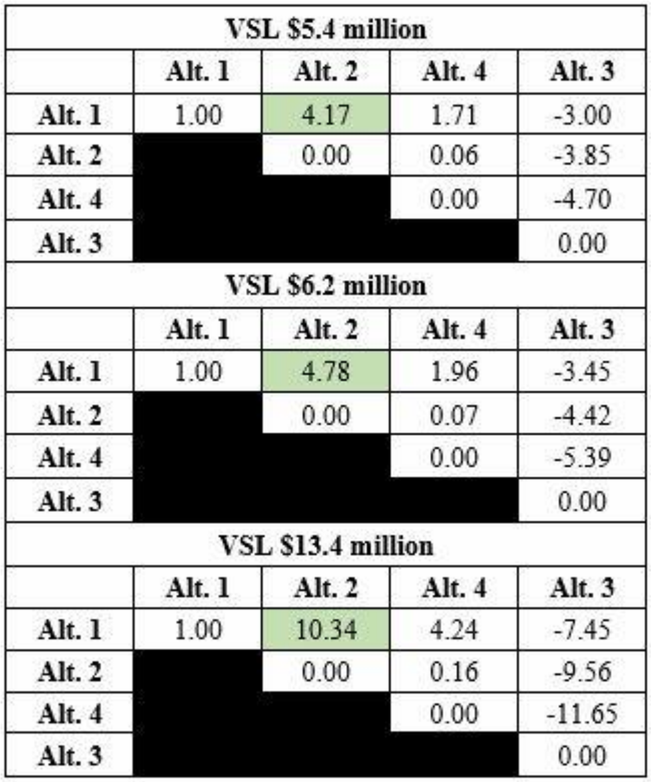
Table D-5 B/C ratios for small pipe median/ramp culverts



VSL $5.4 million				
	Alt. 1	**Alt. 2**	**Alt. 4**	**Alt. 3**
Alt. 1	1.00	3.54	0.71	-8.22
Alt. 2		0.00	-1.51	-9.49
Alt. 4			0.00	-10.77
Alt. 3				0.00
VSL $6.2 million				
	Alt. 1	**Alt. 2**	**Alt. 4**	**Alt. 3**
Alt. 1	1.00	4.07	0.82	-9.44
Alt. 2		0.00	-1.74	-10.90
Alt. 4			0.00	-12.36
Alt. 3				0.00
VSL $13.4 million				
	Alt. 1	**Alt. 2**	**Alt. 4**	**Alt. 3**
Alt. 1	1.00	8.79	1.77	-20.39
Alt. 2		0.00	-3.76	-23.55
Alt. 4			0.00	-26.72
Alt. 3				0.00

APPENDIX E – BENEFIT- COST RATIOS MATRIX FOR SIX-LANE 70 MPH DIVIDED HIGHWAYS

Table E-5 B/C ratios for small pipe median/ramp culverts



VSL $5.4 million

	Alt. 1	Alt. 2	Alt. 4	Alt. 3
Alt. 1	1.00	4.17	1.71	-3.00
Alt. 2		0.00	0.06	-3.85
Alt. 4			0.00	-4.70
Alt. 3				0.00

VSL $6.2 million

	Alt. 1	Alt. 2	Alt. 4	Alt. 3
Alt. 1	1.00	4.78	1.96	-3.45
Alt. 2		0.00	0.07	-4.42
Alt. 4			0.00	-5.39
Alt. 3				0.00

VSL $13.4 million

	Alt. 1	Alt. 2	Alt. 4	Alt. 3
Alt. 1	1.00	10.34	4.24	-7.45
Alt. 2		0.00	0.16	-9.56
Alt. 4			0.00	-11.65
Alt. 3				0.00