In-Service Evaluation of Culvert Extensions

Final Report
March 2020

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16. Abstract

In the United States, nearly 40,000 fatal crashes occur every year, and about one-third of these fatalities involve a vehicle striking a roadside object, such as a culvert, tree, or utility pole. Culverts, specifically, are placed on the roadside to allow water to flow under a road or railroad from one side to the other. Since these are placed close to the travel lanes, they increase the likelihood for a crash to occur or to increase the crash severity.

The American Association of State Highway and Transportation Officials (AASHTO) *Roadside Design Guide* (RDG) suggests some safety treatments to reduce hazards from these structures (i.e., redesign using a traversable design, extend the structure outside the clear zone, shield the cross drainage structure).

Throughout this study, and after a thorough review of current state design practices, the researchers extracted culvert-related information from various resources provided by the Iowa Department of Transportation (DOT), such as their crash, geographic information management system (GIMS), and culvert databases, to determine the risk of crashes involving roadside culverts. Based on the results of these analyses, a related objective was to evaluate the cost-effectiveness of these safety treatments.

The study also involved a survey of state DOTs, highlighting current practices adopted by other transportation agencies throughout the US regarding the protection of culverts.

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IN-SERVICE EVALUATION OF CULVERT EXTENSIONS

Final Report
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1. INTRODUCTION

1.1 Background

In the United States, nearly 40,000 fatal crashes occur every year (NHTSA 2018). About one-third of these fatalities involve a vehicle striking a roadside object, such as a culvert, tree, or utility pole. About 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 shows the run-off-road fatalities by first harmful event for 2012–2016, based on the Fatality Analysis Reporting System (FARS) data (NHTSA 2018).

Table 1. 2012–2016 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**

Source: NHSTA 2018

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:

- 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 the RDG (AASHTO 2011), include the following:

- 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.

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 foreslope of the embankment. For culverts that cannot be made traversable, it is advisable to extend the culvert just outside the clear zone. This reduces the likelihood of vehicles striking the culvert, but will not eliminate the risk 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. 1993).

Another approach is to install a guardrail on sections of roadway where high embankments are present. However, this approach can actually increase the number and cost of crashes, because the guardrail itself also creates a hazard and is installed much closer to the roadway than the culvert opening (Albuquerque et al. 2009). Although the RDG highlights some of the safety treatments to protect culverts, it does not specify when these treatments should be used, or when to select one treatment over another. Furthermore, 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 alternatives discussed previously.

1.2 Research Objectives

The main objectives of this study are to determine the risk of crashes involving roadside culverts and to assess the potential impacts of installing various culvert safety treatments to mitigate crash frequency and severity. 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 departments of transportation (DOTs) that highlights the current practices adopted by other transportation agencies throughout the United States regarding the protection of culverts.

1.3 Report Structure

This report is organized into seven chapters. The remaining chapters are described as follows:

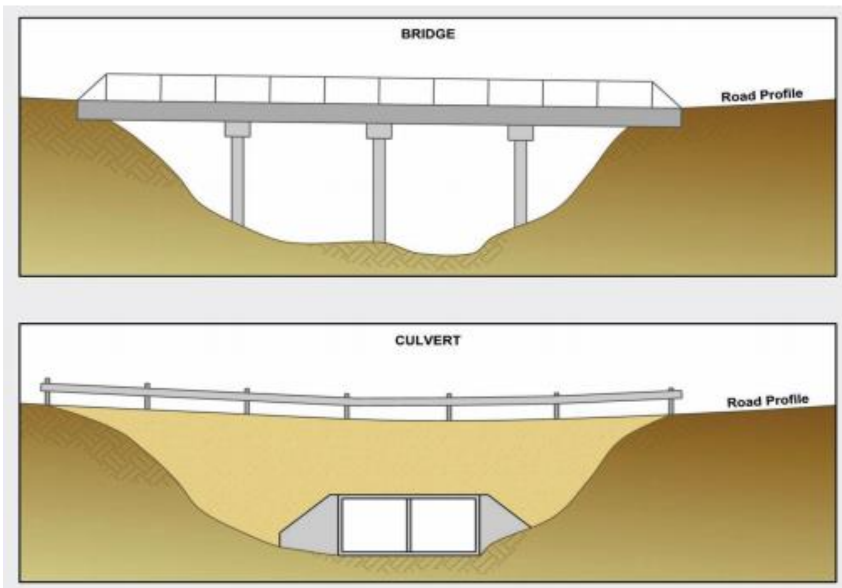
- Chapter 2 discusses design practices by the Federal Highway Administration (FHWA) and AASHTO RDG as well as state design practices, focusing on the Iowa DOT. It also highlights important findings from a survey sent to other state DOTs on their culvert safety practices.
- Chapter 3 provides a detailed review of the existing literature on various culvert safety treatments. It also discusses in detail the practices adopted by the FHWA and 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 their crash database, geographic 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 on 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 a 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 created culvert sizes.
- 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.

2. STATE-OF-THE-PRACTICE REVIEW

This chapter highlights design practices by the FHWA and AASHTO RDG, as well as state design practices, focusing on those of the 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 FHWA has specified guidelines for the planning and hydraulic design of culverts (Schall et al. 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, lifecycle costs, etc. The first consideration is whether a culvert or a bridge is required at a given roadway location, as shown in Figure 1.



Schall et al. 2012, FHWA

Figure 1. Bridge versus culvert

A culvert is installed where it is more economical than a bridge, and where a bridge is not required for reasons of topography, hydraulic requirements, or environmental concerns. The initial cost of building 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 the 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 ft 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.

The safety consideration for a culvert includes the installation of guardrails or longitudinal grates. Regarding the protection of these culverts from errant vehicles, the AASHTO RDG recommends various safety treatments. A detailed description of these safety treatments is discussed in the literature review (Chapter 3).

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 that then is passed on to a designer for the final plan and structural design. For 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 involves 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 most important tasks 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 percent 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 1 ft for entrance culverts to 2 ft 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 a culvert is 1 ft for the median. For precast reinforced concrete boxes (RCBs), the minimum cover from the edge of the shoulder is 2 ft, however, less than 2 ft cover is allowed for cast-in-place RCBs.

Concrete pipe culvert diameters generally range from 18 to 84 in. in 6 in. 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 in.

The Iowa DOT specifies that a concrete pipe should be used if a highway has more than 3,000 vehicles average daily traffic (ADT) or if the highway is part of the National Highway System (NHS), including county or city roadways. For highways less than 3,000 vehicles ADT that are not part of the NHS, unclassified roadway pipe (coated corrugated metal pipe [CMP] or high-density polyethylene [HDPE] pipe) is specified. 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 US 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 as 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 shows a map of the states that participated in the survey.

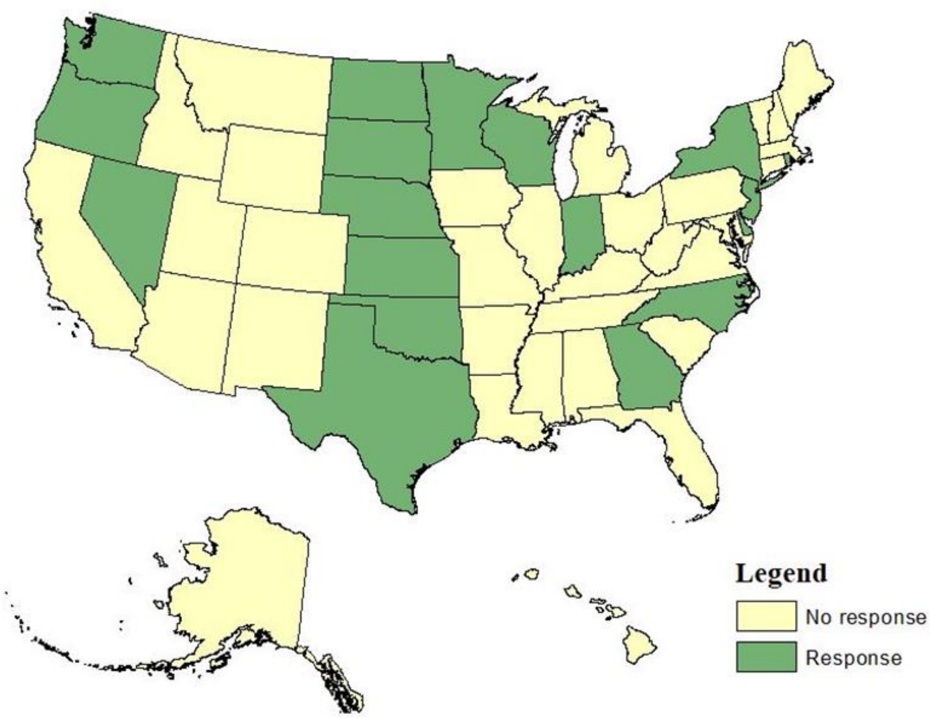


Figure 2. States that participated in the survey

Figure 3 shows 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.

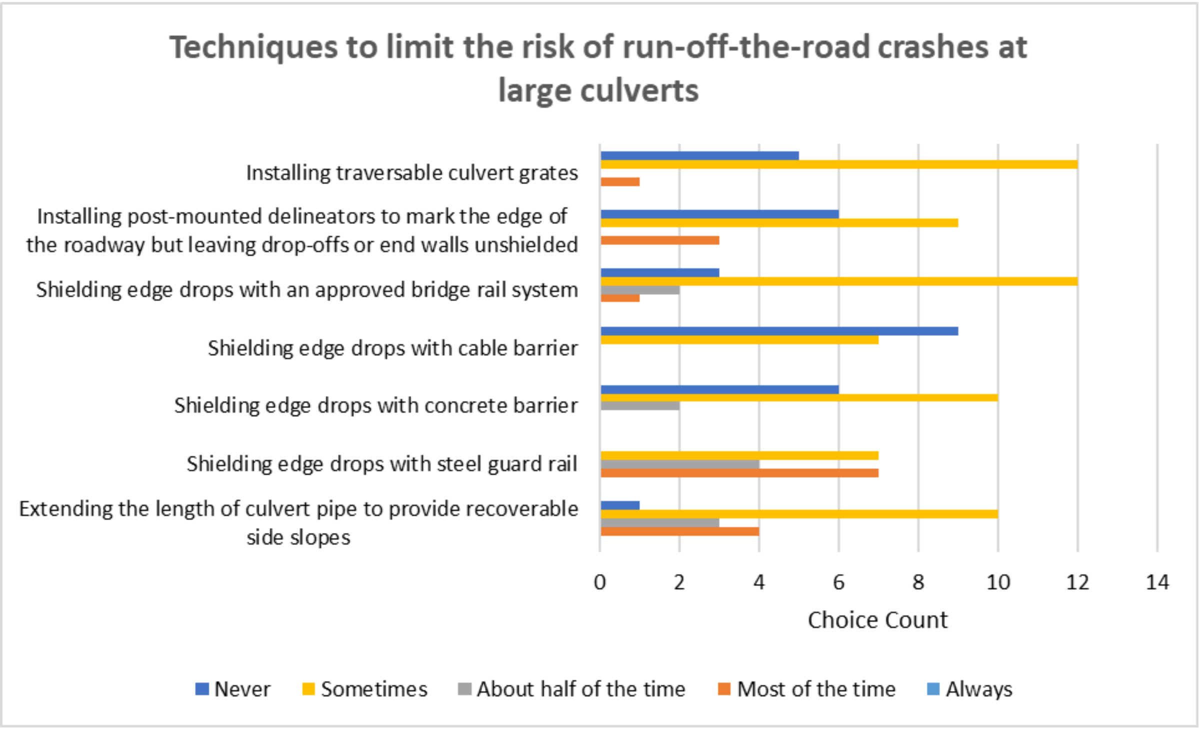


Figure 3. Selection of techniques to limit the risk of run-off-road crashes at large culverts

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.

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 4 shows the factors highlighted by the respondents that affect the selection of protective treatment.

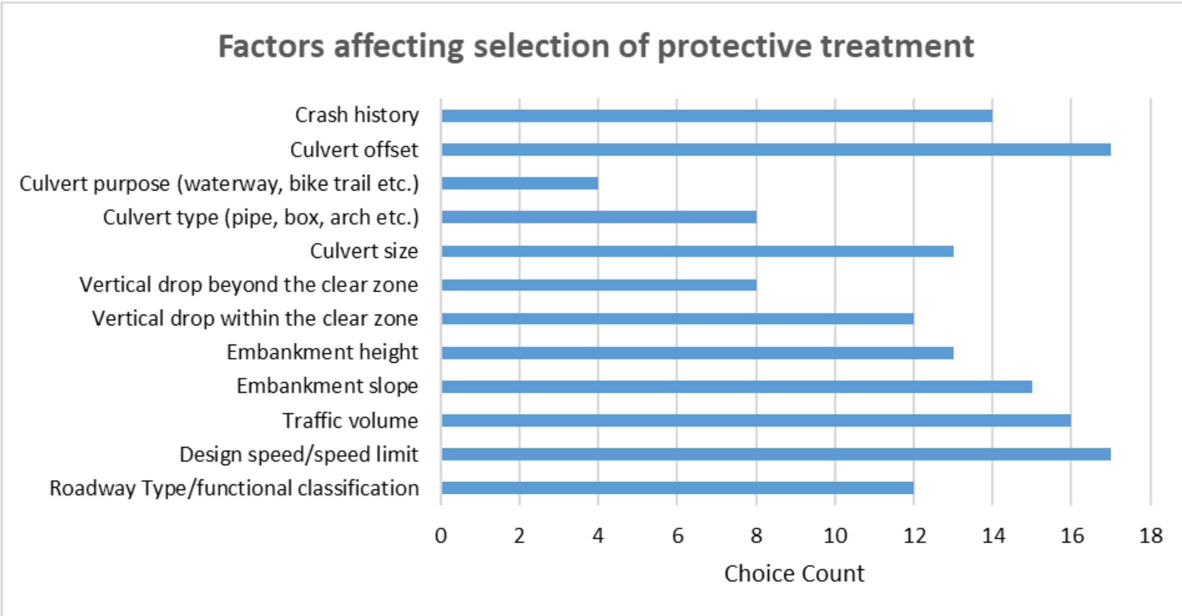


Figure 4. Factors affecting selection of protective treatment

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.

3. LITERATURE REVIEW

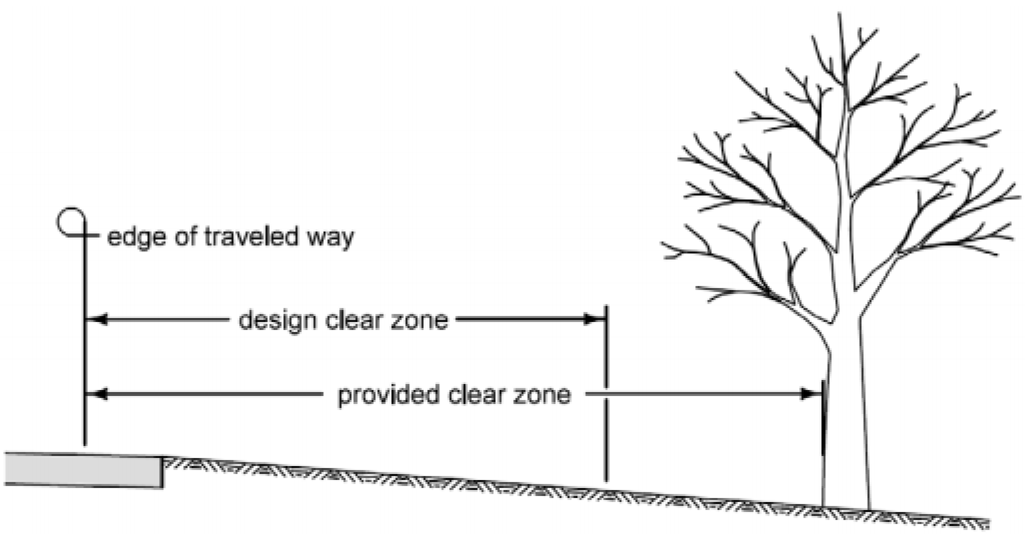
This chapter provides a detailed review of the existing literature on various culvert safety treatments. It also discusses in detail the practices adopted by the FHWA and Iowa DOT. In addition, it explains the incremental benefit-cost analysis to examine the cost effectiveness of these safety treatments.

3.1 Culvert Opening Safety Treatments

The existing preferred options for treating a culvert opening include the following:

1. Eliminating the opening
2. Extending or relocating the culvert beyond the clear zone
3. Treating the opening to make it traversable
4. 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 5.



Iowa DOT 2017a

Figure 5. Clear zone concept for roadside obstacles

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.

Cross drainage culverts having diameters larger than 36 in. 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 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 RDG, the width of the clear zone ranges from 2 m (7 ft) to 14 m (46 ft) depending on roadway design speed, slope, design traffic volume, and horizontal curvature, as shown in Table 2.

Table 2. Recommended clear zone distances from edge of the traveled lane (ft)

		Foreslopes			Backslopes		
Design Speed	**Design ADT**	**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
	750–1,500	10–12	12–14	–	12–14	12–14	12–14
	1,500–6,000	12–14	14–16	–	14–16	14–16	14–16
	Over 6,000	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
	750–1,500	14–16	16–20	–	10–12	12–14	14–16
	1,500–6,000	16–18	20–26	–	12–14	14–16	16–18
	Over 6,000	20–22	24–28	–	14–16	18–20	20–22
55 mph	Under 750	12–14	14–18	–	8–10	10–12	10–12
	750–1,500	16–18	20–24	–	10–12	14–16	16–18
	1,500–6,000	20–22	24–30	–	14–16	16–18	20–22
	Over 6,000	22–24	26–32	–	16–18	20–22	22–24
60 mph	Under 750	16–18	20–24	–	10–12	12–14	14–16
	750–1,500	20–24	26–32	–	12–14	16–18	20–22
	1,500–6,000	26–30	32–40	–	14–18	18–22	24–26
	Over 6,000	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
	750–1,500	24–26	28–36	–	12–16	18–20	20–22
	1,500–6,000	28–32	34–42	–	16–20	22–24	26–28
	Over 6,000	30–34	38–46	–	22–24	26–30	28–30

Source: AASHTO 2011, Roadside Design Guide

Slopes steeper than 1V:3H are not recommended by the RDG.

Studies conducted by 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.

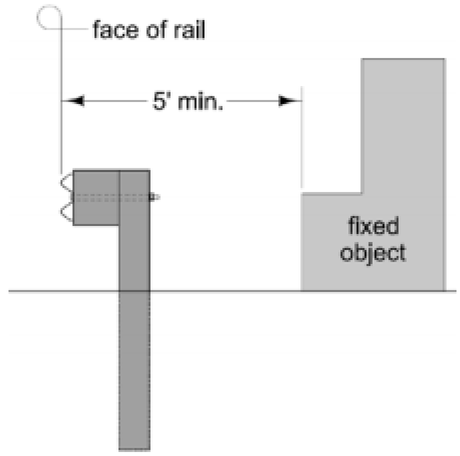
For the purpose of this project, the highest value of clear zone width within each range of design speed and design traffic volume was used. For example, for a road segment with design speed of 55 mph and design traffic volume over 6,000, the average clear zone distance of 24 ft was used for a foreslope 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 et al. 2012). However, many of these barrier systems are too weak to protect run-off-road vehicles from penetrating the barrier and striking the culverts. In some cases, these barriers pose an even greater threat than leaving the culvert opening unprotected.

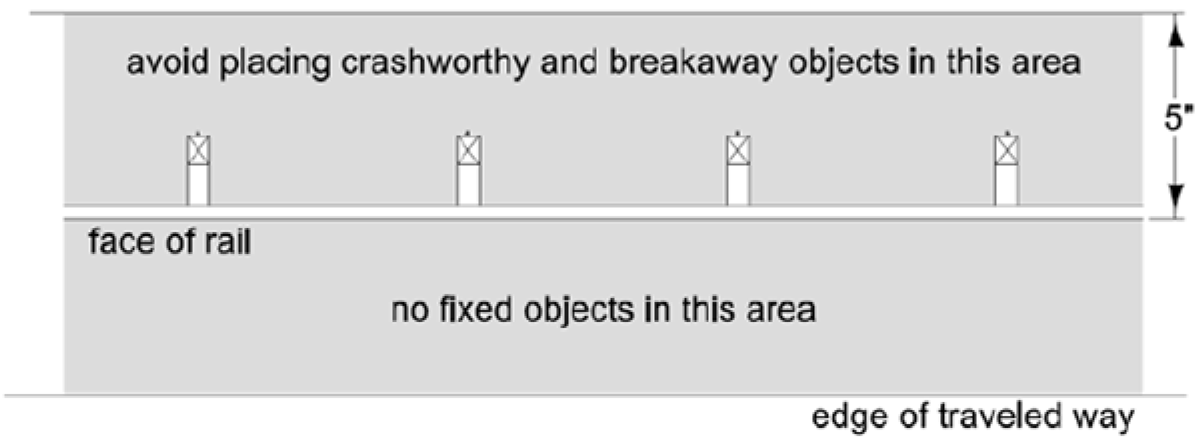
One of the most common used barriers to protect roadside obstacles is the steel beam guardrail. According to Section 8C-2 of the *Iowa DOT Design Manual*, the Iowa DOT uses the Midwest Guardrail System (MGS) at a mounting height of 31 in. The steel beam guardrail is a semi-rigid barrier, which implies that the barrier deflects up to a certain extent. During a crash, the steel beam guardrail can deflect up to as much as 4 ft. Therefore, it results in higher crash forces than a flexible barrier such as a cable guardrail. A distance of at least 5 ft should be provided (Iowa DOT 2017c) between the guardrail and a fixed object, as shown in Figure 6.



Iowa DOT 2017c

Figure 6. Guardrail placement near a fixed object

As much as possible, guardrail terminal ends should not be placed near fixed objects, as shown in Figure 7.

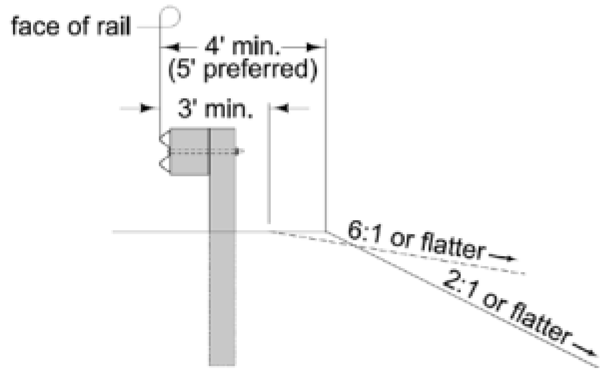


Iowa DOT 2017c

Figure 7. Placement of fixed objects behind guardrail

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.

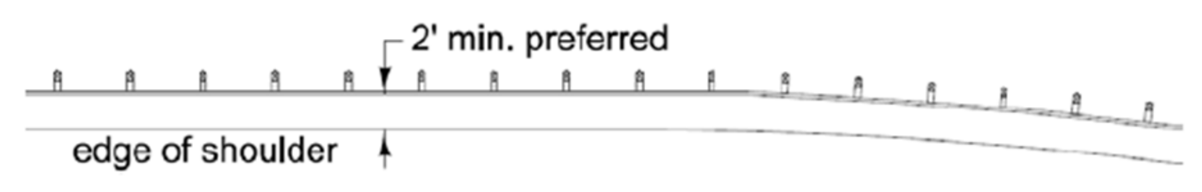
Generally, it is advisable to place guardrails on foreslopes of 10:1 or flatter. However, guardrails can be placed on foreslopes 2:1 or flatter with a minimum gap of 4 ft (5 ft preferred) between the slope and face of guardrail. This minimum gap can be reduced to 3 ft for foreslopes 6:1 or flatter, as shown in Figure 8.



Iowa DOT 2017c

Figure 8. Guardrail placement near foreslopes

Another important consideration 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 ft plus the width of the shoulder (or 2 ft from the edge of the shoulder) is preferred as the guardrail offset, as shown in Figure 9.



Iowa DOT 2017c

Figure 9. Guardrail offset from the edge of shoulder

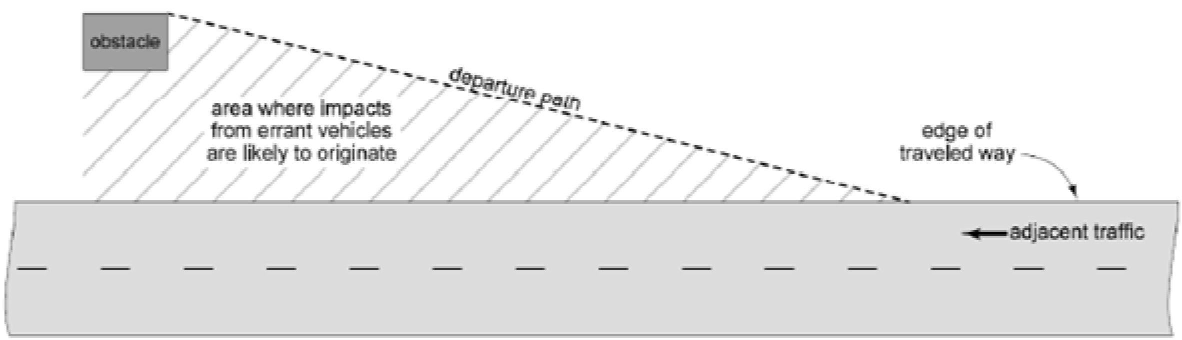
This is different from the "shy-line offset" (L_S), which is the offset distance beyond which an object will not be perceived by drivers as a hazard. In general, the guardrail offset should be greater than the shy-line offset. Table 3 shows the shy-line offset values as suggested by the RDG.

Table 3. Suggested shy-line offset for guardrails

Design Speed (mph)	Shy Line Offset (L_S) (ft)
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

Source: AASHTO 2011, *Roadside Design Guide*

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 10.



Iowa DOT 2011

Figure 10. Vehicle departure path and its associated area

The location of this path is essential in determining 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 further a barrier is located from the edge of the roadway, the shorter the length will be.

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 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

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:

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

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 striking 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 11.

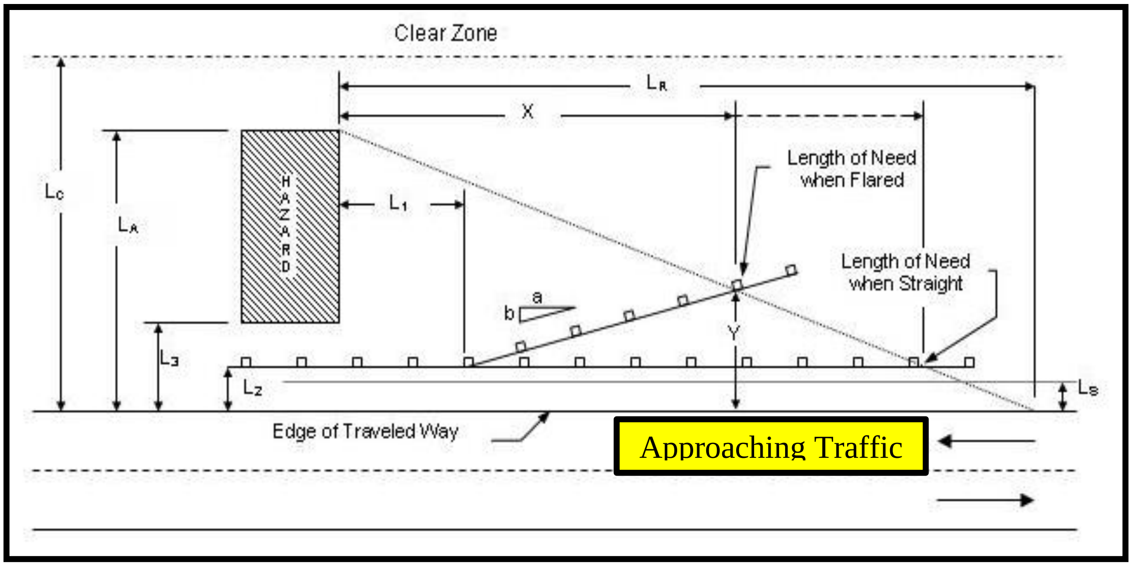


Figure 11. Guardrail LON for approaching traffic

These values vary based on speed limit and traffic volume, as shown in Table 4.

Table 4. Runout length table for guardrails

Design Speed (mph)	Traffic Volume			
	ADT ≥ 10,000	5,000 ≤ ADT < 10,000	1,000 ≤ ADT < 5,000	ADT < 1,000
	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

Source: AASHTO 2011, *Roadside Design Guide*

Equation (2) is used for both the upstream and downstream lengths of guardrails, the only difference being that an additional lane width (12 ft) 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 12.

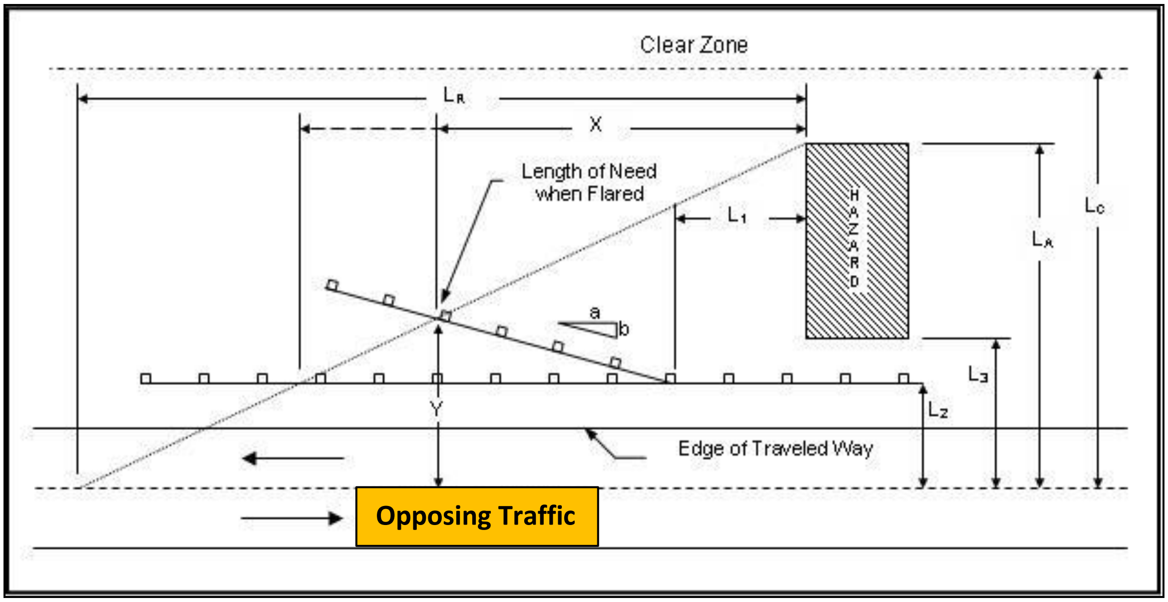


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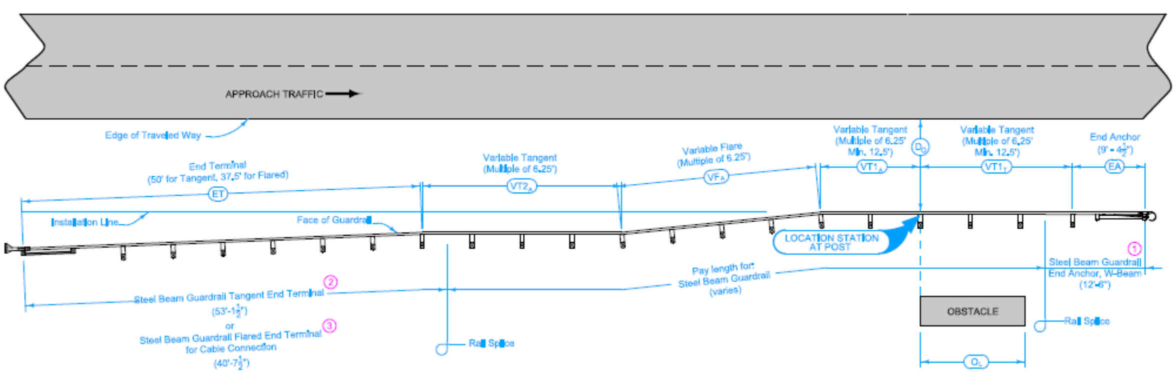
Figure 12. Guardrail LON for opposing traffic

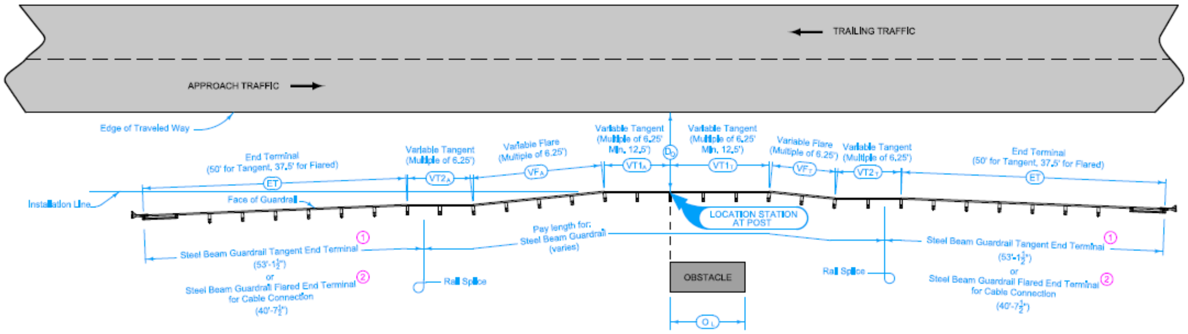
The LON for guardrails was calculated using this equation in a macro-enabled excel sheet provided by the FHWA (FHWA 2018).

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 13, for one-way protection, and Figure 14 for two-way protection.



Iowa DOT 2016c

Figure 13. Steel beam guardrail installation at side obstacle (one-way protection)

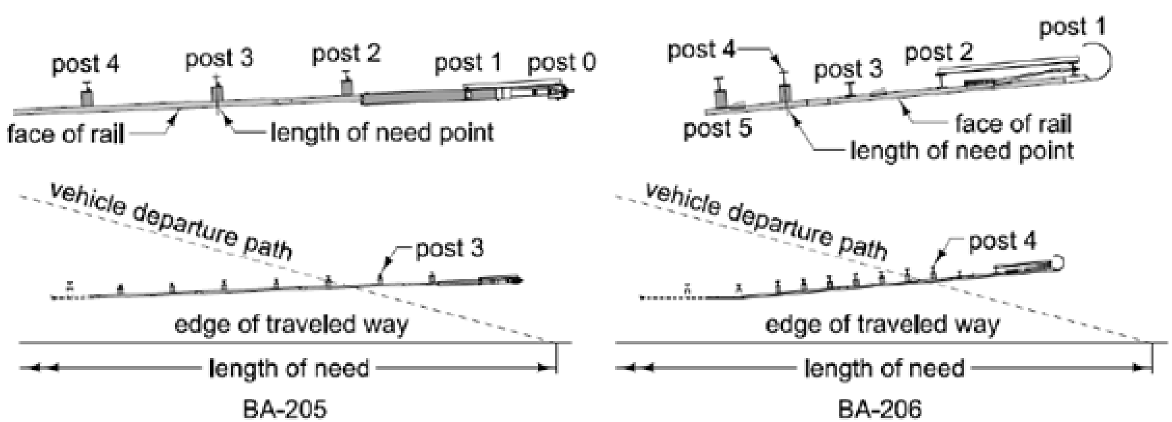


Iowa DOT 2016d

Figure 14. Steel beam guardrail installation at side obstacle (two-way protection)

These end terminals are placed on both approach and trailing ends of the guardrail for two-lane roads, and on approach ends only for divided roads. The length of the guardrail terminal sections are 53 ft 1.5 in. for a tangent end terminal or 40 ft 7.5 in. for a flared end terminal (Iowa DOT 2016d). BA-205 (Iowa DOT 2016e) contains details on steel beam guardrail tangent end terminals (MASH TL-3) and BA-206 (Iowa DOT 2016b) contains details on steel beam guardrail flared end terminals 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. For 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 ft 6 in.

As shown in Figure 15, the LON point for BA-205 is at post 3, whereas for BA-206, it is at post 4.



Iowa DOT 2017c

Figure 15. Length of need point for end terminals

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.

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 16 shows a commonly used safety grate for a pipe culvert.

Hitesh Chawla, CTRE

Figure 16. Commonly used safety grate for a pipe culvert

Two full-scale crash tests were performed on a 21 x 21 ft culvert to examine the safety performance of culvert grates when installed on slopes as steep as 1V:3H (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 the RDG.

Table 5 and Figure 17 show the guidelines for installing longitudinal grates on cross-drainage culverts.

Table 5. Suggested inside diameter for varying span lengths of grates

Span Length (ft)	Inside Diameter (in.)
Up to 12	3.0
12–16	3.5
16–20	4.0
20 or less with center support	3.0

Source: AASHTO 2011, Roadside Design Guide

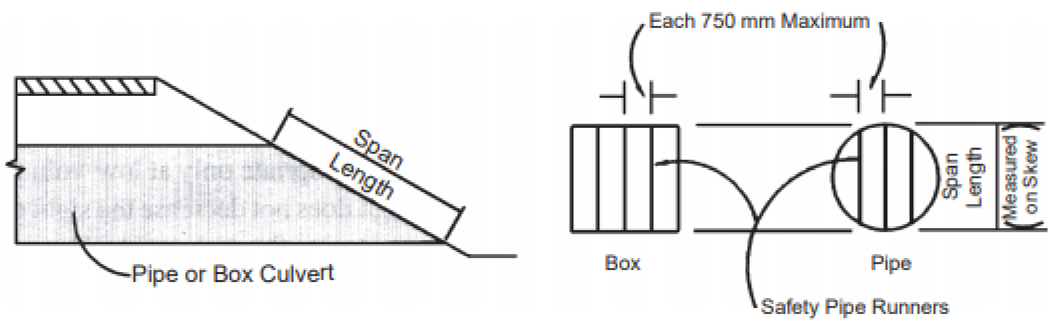


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Figure 17. AASHTO Roadside Design Guide longitudinal grate guidelines

These guidelines were developed by Ross et al. (1982) and later included in the RDG. The inside diameter of the rebar to be used depends on the span length of the culvert (either box or pipe).

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, Sicking and Wolford 1996, Wolford and 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 a 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 an incremental benefit-cost ratio (BCR):

$$\mathrm{BCR}_{12} = \frac{CC_1 - CC_2}{DC_2 - DC_1} \tag{3}$$

where,
BCR_{12} = Incremental BCR of Alternative 2 to Alternative 1
CC_1, CC_2 = Annualized crash costs for Alternatives 1 and 2
DC_1, DC_2 = Annualized 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 BCR exceeds 1. If the BCR 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.

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 their crash database, geographic information management system (GIMS), and culvert database. 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 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 GIMS roadway database. This database contains different data sets pertaining to roadway information. Each row in the data set represents a segment of the roadway. For example, the GIMS database for 2015 contains a data set file that has the average annual daily traffic (AADT) information as well as the distribution of AADT among different vehicle classes in 2015. Similarly, a lane data set file contains information regarding speed limit, shoulder widths, presence of rumble strips, etc. for both directions of travel lanes, while a road info data set file contains information regarding the number of lanes, presence of median, median type, lane type, etc. on a particular segment. All of 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 18 shows the accuracy of a georeferenced GIMS road segment with available aerial imagery from ArcGIS.

Figure 18. GIMS road segment accuracy

4.1.2 Culvert Database

The culvert data set 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 was installed, location (x and y coordinates), etc. The completeness of the data set was evaluated by mapping the culvert data set in ArcGIS onto a map of primary road networks obtained from the Iowa DOT GIMS database.

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

With the data set 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 were then 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 database, ArcGIS was used to cross-reference the barrier data with the culvert data to determine the percentage of existing culverts that were being protected by some kind of barrier.

After determining the culverts 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 data sets 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 crashes.

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:

1. The two fields “Crash Sequence of Events” and “First Harmful Event” were filtered for the value “Culvert” in the crash database.
2. 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 “First Harmful Event” found 1,206 crashes, while searching “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 data set to only those occurring on the primary road network (interstates, US highway system, and state highway system). This was accomplished by filtering the “SYSTEM” field, wherein “1” represented interstates, “2” represented the US highway system, “3” represented the state highway system, and “4” to “9” represented other roadway types. After applying these criteria, 872 culvert-related crashes on the primary road network were 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 of 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 to 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 the primary road network were selected, using the same filtering criteria as described previously for searching crash codes. Overall, 435 culvert-related crashes were identified by searching 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 culvert installation and repair, guardrail installation and maintenance, and safety grate 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 for 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 19.

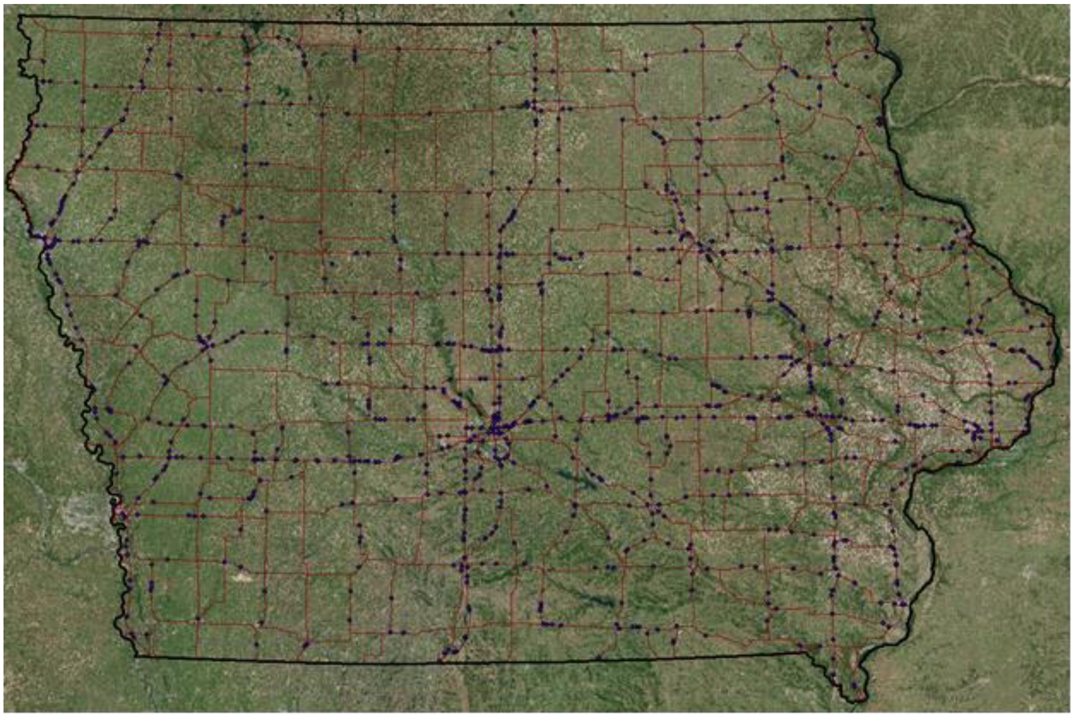


Figure 19. Distribution of 1,132 culvert-related crashes across Iowa

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 couple of reasons to choose this buffer distance as 500 m: the units of the coordinate system used in ArcGIS were meters, and 500 m was chosen visually to encompass as many of the crashes as realistically possible.

4.2.1 Culvert Data Summary

The combined database included both transverse and parallel culverts. Because parallel culverts were 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 data set after filtering based on this criterion consisted of 568 observations. The length attribute of the missing culverts in this final data set was completed to the extent possible using the Ruler tool in Google Earth, as shown in Figure 20.

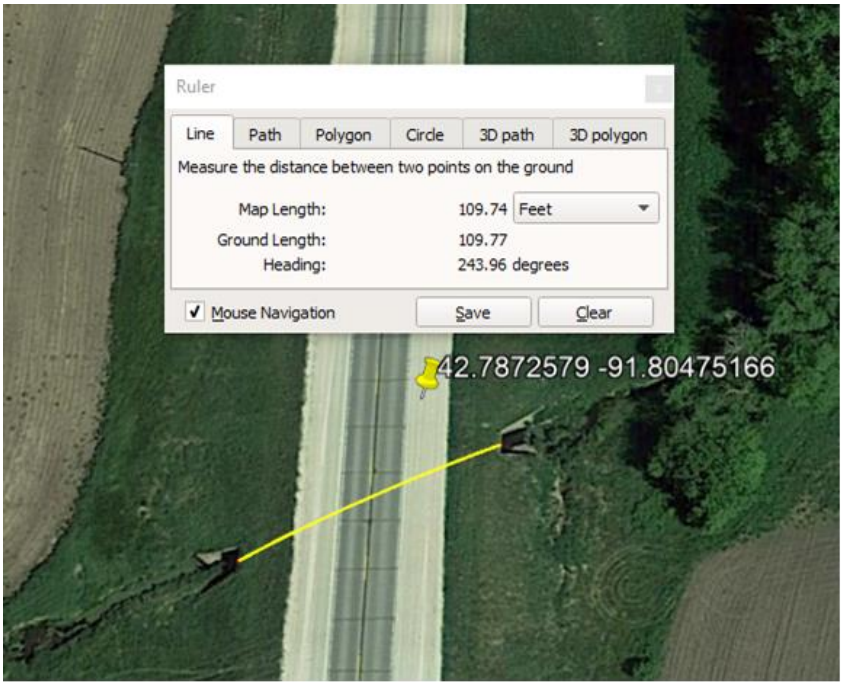


Figure 20. Length of culvert measured manually in Google Earth

Table 6 provides the data summary for 547 cross-drainage culverts that were found to experience 568 crashes over the duration of the 10-year study period.

Table 6. Summary statistics for the 547 perpendicular (cross-drainage) culverts

Variable	Category	Count	Percentage (%)
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
Distance to nearest culvert (feet)	<100	172	31.44
	100–200	163	29.80
	200–500	150	27.42
	500–1,000	43	7.86
	1,000–1,500	16	2.93
	≥1,500	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

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.

For the purpose of this study, culverts were divided into different categories based on their sizes and shapes. These include the following:

- Small pipe culverts: Pipe culverts with a diameter less than 4 ft
- Medium pipe culverts: Pipe culverts with a diameter between 4 ft and 10 ft
- Medium box culverts: Box culverts with a width between 4 ft and 10 ft
- Large box culverts: Box culverts with a width greater than 10 ft

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

4.2.2 Crash Data Summary

One of the most important fields in the crash data was crash severity, which was 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 7 shows the summary statistics of the final data set of culvert-related crashes based on this roadway classification, which excludes the missing values.

Table 7. Crash severity distribution based on roadway classification

	Roadway Classification (%)		
Crash Severity	**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

The three road classifications were seen to have almost the same average crash severities. About 71 to 74 percent of crashes that occurred during the analysis period were either PDO or possible injury crashes, about 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 21.

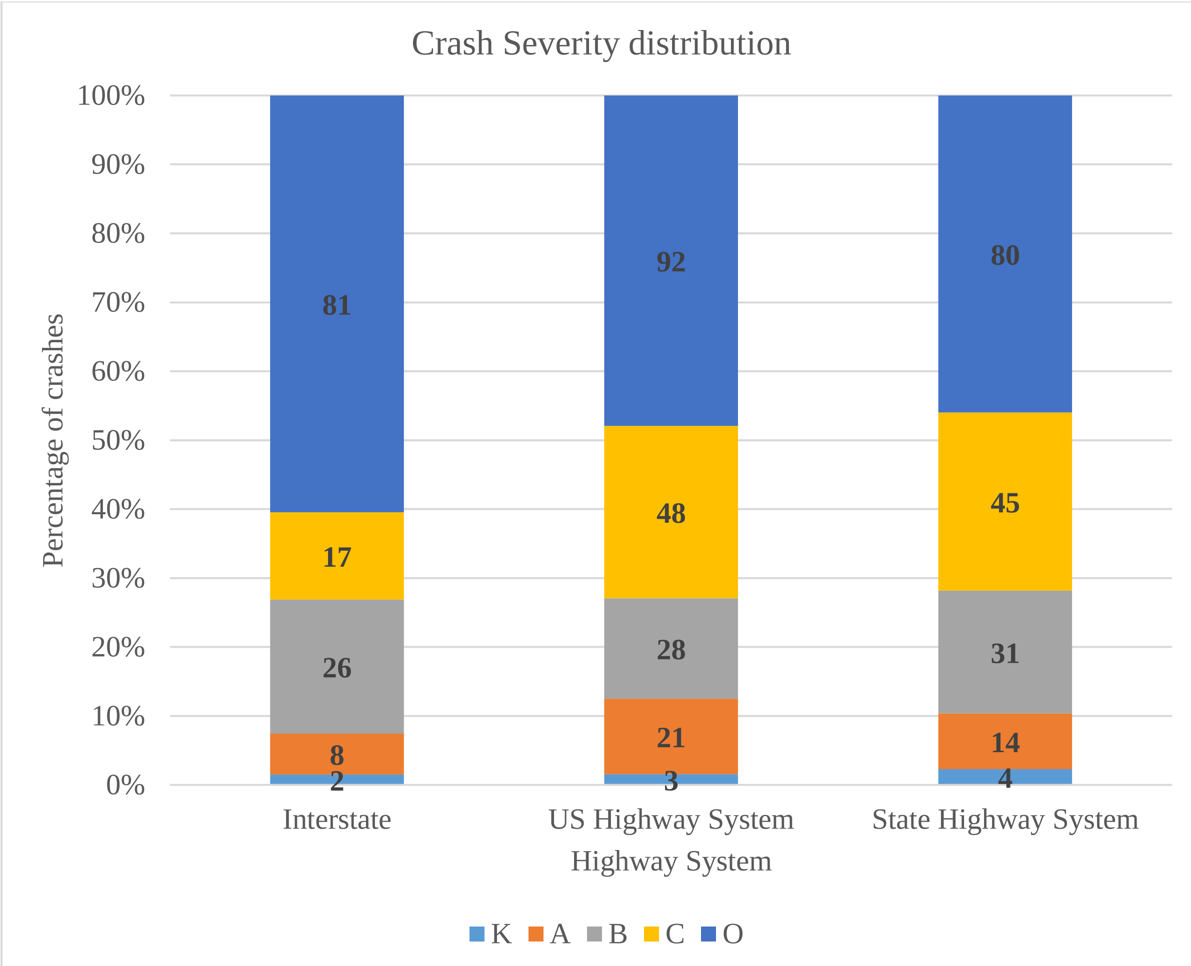


Figure 21. Crash severity distribution based on roadway classification

5. METHODOLOGY

This chapter discusses the methods for calculating crash rates based on different classifications of roadway. It also provides a detailed description of 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 data set 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:

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

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:

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

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 the GIMS database for the years 2007 to 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, simulation software was required 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

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 AASHTO's *Roadside Design Guide* (Ray et al. 2012). Various releases of RSAP have been distributed with the AASHTO 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-crash 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) 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 (Ray et al. 2012).

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.

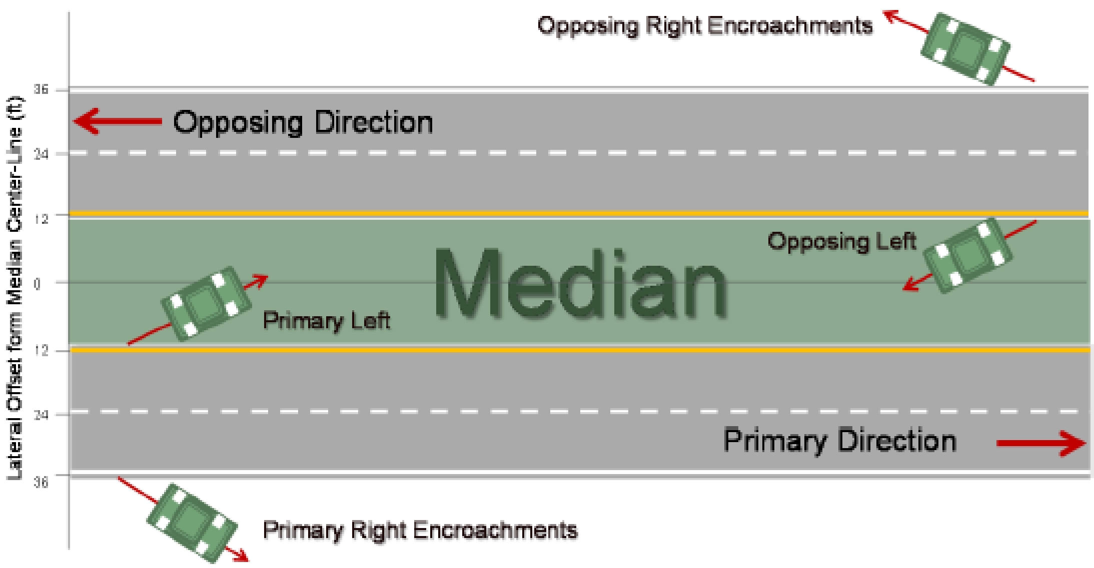
RSAPv3 defines highway types as four-lane divided, two-lane undivided, and one-way highways. Cooper (1980) estimated the default values for a baseline condition, which were derived from extensive data collection and analysis on different highway types and traffic volume (AADT) (Cooper 1980, Ray et al. 2012). 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 ft.
- 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:

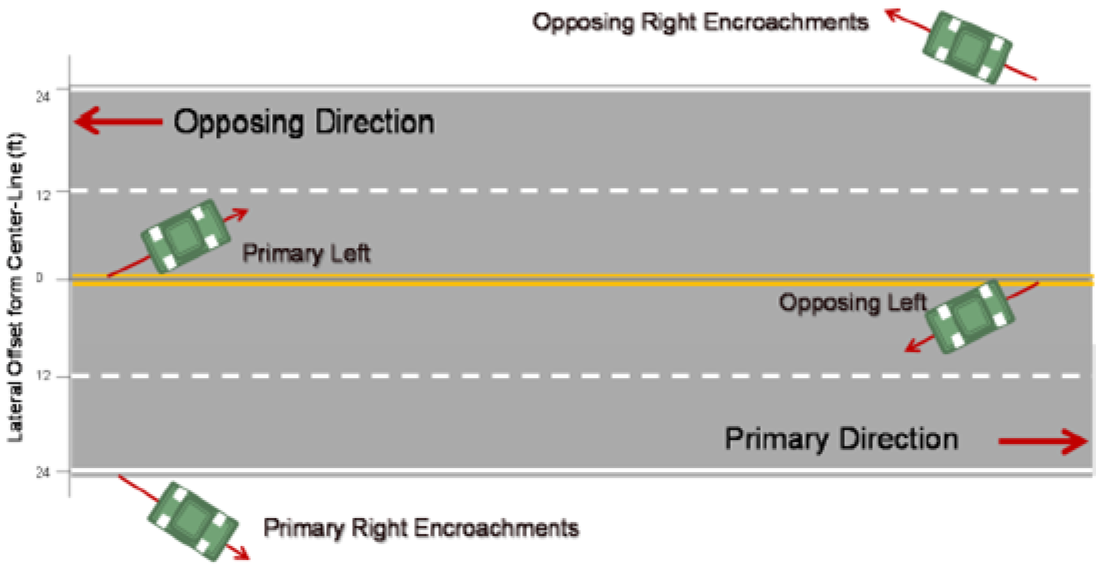
1. Primary direction right encroachment
2. Primary direction left encroachment
3. Opposing direction right encroachment
4. Opposing direction left encroachment

For a two-lane undivided highway, the possible encroachments are the same as those for a divided highway. Figure 22 and Figure 23 illustrate the four possible encroachments for a four-lane divided and two-lane undivided highway, respectively.



Ray et al. 2012, NCHRP

Figure 22. Possible encroachments for a four-lane divided highway



Ray et al. 2012, NCHRP

Figure 23. 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 the 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: 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 realistic 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 (Ray et al. 2012). 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 (Ray et al. 2012). 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 crash occurs: complete stop, hazard penetration, or vehicle redirection. For 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 crashes do not result in penetration or redirection, a percentage of the total crashes that result in a 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

Two different scenarios were designed in RSAP based on the common site types from Table 6 and using the data provided in Table 8.

Table 8. 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)	$4.5 million
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

These scenarios were as follows:

- Two-lane undivided highways with a speed limit of 55 mph
- Four-lane divided highways with a speed limit of 70 mph

All cross-drainage culverts were divided into two categories:

1. Crossing culverts: Culverts that ran under all lanes of travel
2. Median culverts: Culverts that ran under one direction of travel

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).

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). The RSAP *User's Manual* defines the value of statistical life (VSL) as "the average comprehensive crash cost of a fatal crash" (Ray et al. 2012). In this study, the cost per fatality of $4.5 million suggested by the Iowa DOT was used as the VSL value (Harmon et al. 2018, Iowa DOT 2018b).

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 ft on both sides for undivided highways, or 6 ft and 10 ft respectively for the median and outside shoulders for divided highways.

The AADT used in the RSAP program varied between the two scenarios. For two-lane undivided highways, AADT ranged from 1,000 to 9,000 vpd, with an increment of 2,000 vpd. For the four-lane divided highway scenario, the AADT value utilized was 10,000 to 50,000 vpd, with an increment of 10,000 vpd. (Note that the ranges fell within the on-site minimum and maximum values for AADT for each scenario.)

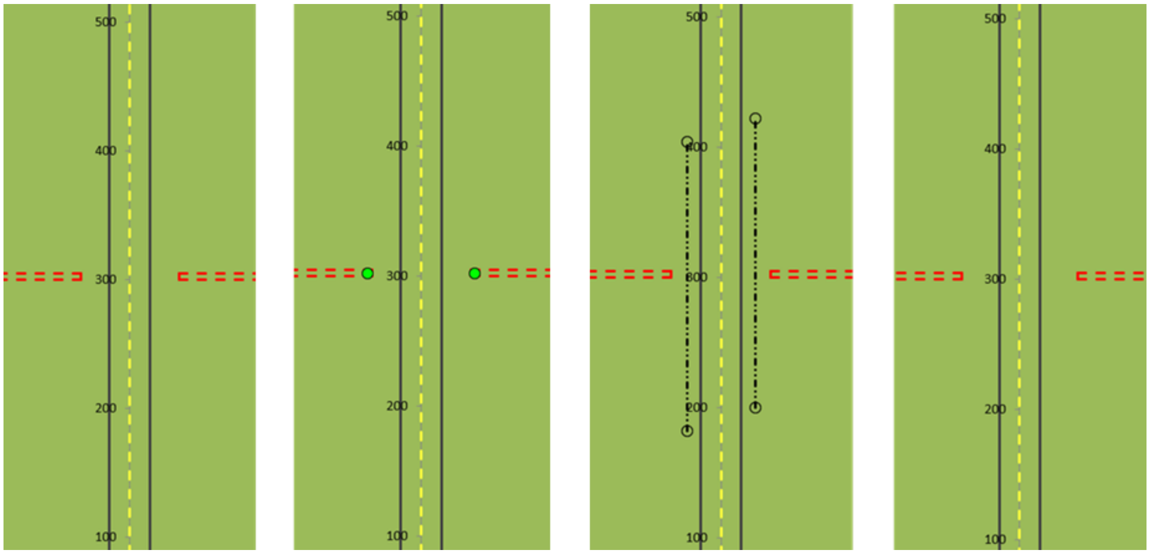
In addition, culvert offsets also varied between the two scenarios. The offset values for two-lane undivided highways ranged from 8 to 32 ft with an increment of 6 ft. For four-lane divided highways, the offset values varied from 14 to 34 ft with an increment of 5 ft. The maximum threshold for the culvert offset for both scenarios was based on the clear zone length.

5.2.3 Alternatives

Four alternatives were defined for each scenario:

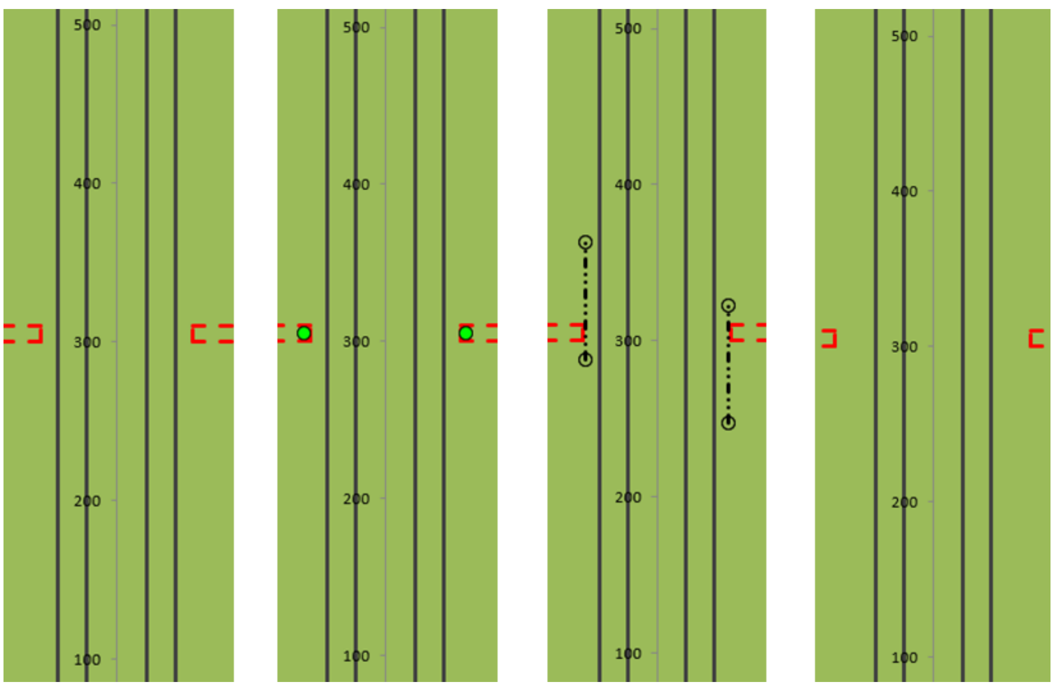
- Do nothing (base)
- Protect the culvert using safety grates
- Protect the culvert using steel beam guardrail
- Extend the culvert outside the clear zone

All these alternatives are illustrated in Figure 24 for two-lane undivided highways, in Figure 25 for four-lane divided highways, and in Figure 26 for median culverts.



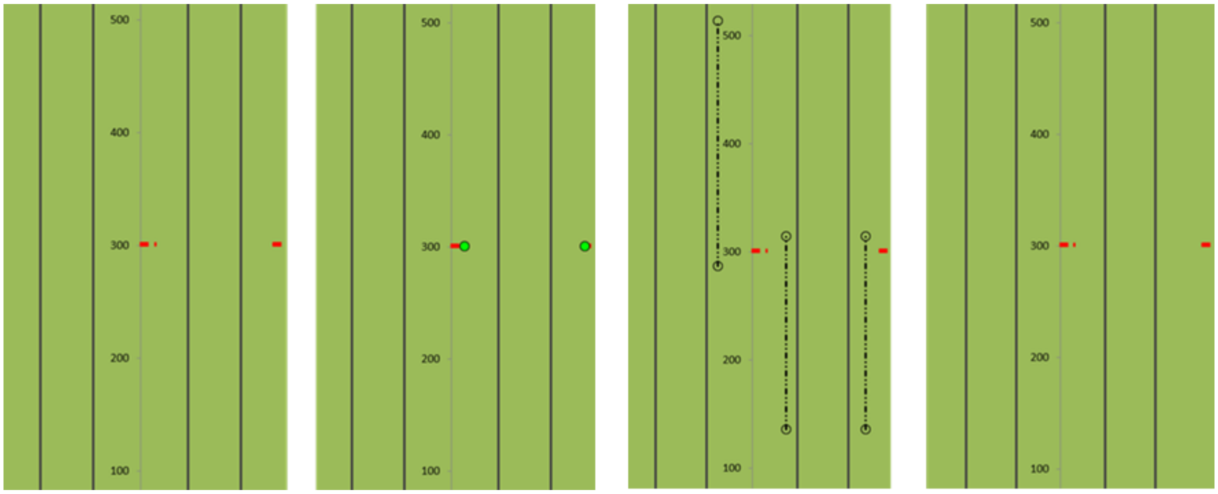
(a) Do Nothing **(b) Safety Grates** **(c) Guardrail** **(d) Culvert Extension**

Figure 24. RSAP alternatives for medium pipe culvert on two-lane 55 mph undivided highway



(a) Do Nothing **(b) Safety Grates** **(c) Guardrail** **(d) Culvert Extension**

Figure 25. RSAP alternatives for large box culvert on four-lane 70 mph divided highways



(a) Do Nothing **(b) Safety Grates** **(c) Guardrail** **(d) Culvert Extension**

Figure 26. RSAP alternatives for a small pipe median culvert on four-lane 70 mph divided highways

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.

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.

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 (USDA 2011). Since RSAP does not have any element to represent a grate, a generic fixed object of diameter equal to the width of the culvert was provided at the mid-width of the culvert.

5.2.3.3 Protect the Culvert Using Steel Beam Guardrail

This alternative required a long length of guardrail 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 the 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).

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 an item number, description, and a low, high, and average cost price for the items. Pipe culvert sizes ranged from 18 to 90 in., while box culvert sizes ranged from 4 to 14 ft. Given this study was limited to cross-drainage culverts, entrance pipe culverts, and corrugated pipe culverts, 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 9.

Table 9. Culvert installation costs

	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

Source: Iowa DOT

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.

The Iowa DOT also provided costs for guardrail (Table 10) and safety grates (Table 11).

Table 10. Guardrail installation costs

Guardrail type	Installation cost		
	Guardrail (LF)	End anchor (each)	Tangent end terminal (each)
Steel beam guardrail	$21.97	$1,259.44	$2,358.48

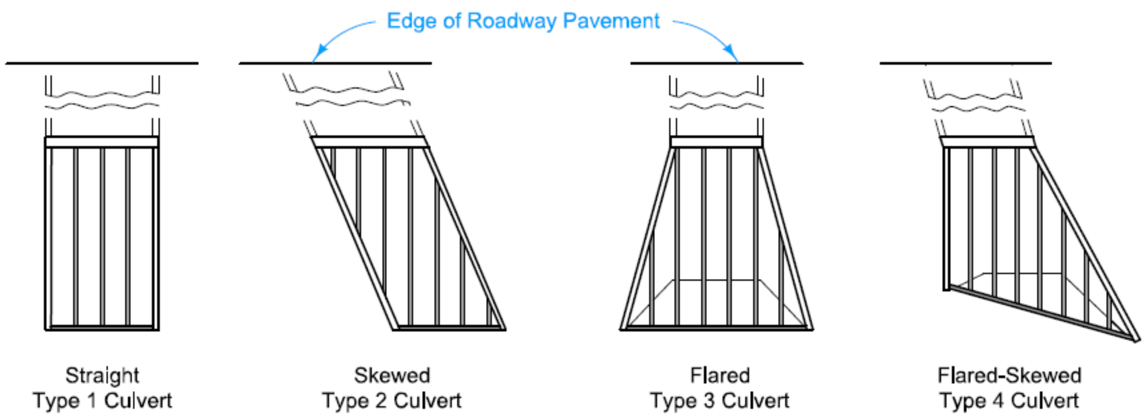
Source: Iowa DOT

Table 11. Safety grate installation costs

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**

Source: Iowa DOT

As can be seen in Table 11 and Figure 27, four different types of grates are used by the Iowa DOT for protecting roadside culverts.



Iowa DOT 2019

Figure 27. Configurations for different types of safety grates

Note that the grate bars in each of these configurations are designed to be perpendicular to the direction of traffic flow.

The data provided by Iowa DOT did not include information about cost relative to the size of the safety grate. Online sources were consulted to obtain these costs (Haala Industries 2018). Table 12 shows the safety grate costs for different sizes of culverts that were used in RSAP.

Table 12. 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

Source: Haala Industries 2018

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 13 highlights the average and median repair costs provided by Iowa DOT with varying culvert types and sizes.

Table 13. Culvert repair costs

	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

Source: Iowa DOT

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 14 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).

Table 14. Crash rates for different highway systems

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

As mentioned earlier, the sum of the 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.

The crash rates were also calculated for the two different scenarios as shown in Table 15.

Table 15. Crash rates for different scenarios

System	Number of crashes	Crash rate (per HMCV)
Two-lane 55 mph undivided highways	192	0.4331
Four-lane 70 mph divided highways	82	0.0655

Two-lane undivided highways with a posted speed limit of 55 mph experienced a higher crash rate (0.4331 per HMCV) compared to the four-lane divided highways with a posted speed limit of 70 mph. The low crash rates for four-lane divided highways (0.0655 per HMCV), as seen in Table 14, is likely due to the typically higher design standards, as all 70 mph segments are part of the interstate system. While about two-thirds of road segments of the two-lane highways belong to the state highway system, hence contributing to the high crash rate.

Ultimately, the preceding data from this in-service evaluation provides several insights into the prevalence of culvert-involved crashes throughout Iowa. However, given the limited sample size of culvert-involved crashes, as well as the degree of imprecision associated with the spatial location of traffic crashes in proximity to culverts, it is not feasible to distinguish the potential safety impacts of various culvert safety treatments based upon these data.

Further, research suggests that to completely remove the potential sources of bias from an in-service performance evaluation, both reported and unreported crashes would need to be analyzed (Mak and Sicking 2002). Unreported crashes need to be considered because they represent the "successes" of the roadside safety treatment as these crashes likely result in neither injury nor serious property damage. Studies have attempted to estimate the number of unreported crashes based on maintenance records (Carlson et al. 1978), video camera surveillance (Fitzpatrick et al. 1999), and periodical inspections (Ray and Weir 2001, Galati 1967).

6.2 Roadside Safety Analysis Program (RSAP) Evaluation

Given the aforementioned limitations, the FHWA's Roadside Safety Analysis Program (RSAP) was used to compare the relative safety performance of various culvert safety treatments under a range of conditions. Based upon the various scenarios that were described in Chapter 5, a total of 224 different RSAP models were created. These models were developed based on different AADTs, culvert offsets, and types of culverts. The threshold used for the benefit-cost ratio in selecting the best alternative in each model is two. The following sections present the cost-effective analyses. Additional details are provided in Appendices A and B.

6.2.1 RSAP Scenario 1: Two-Lane 55 MPH Undivided Highways

Table 16 shows the RSAP results for two-lane 55 mph undivided highways where all the culverts in this scenario were crossing culverts.

Table 16. Best case alternatives for two-lane 55 mph undivided highways

Culvert type	AADT	Offset (feet)				
		8.0	14.0	20.0	26.0	32.0
Small pipe crossing	1,000	CE	CE	DN	DN	DN
	3,000	CE	CE	CE	SG	SG
	5,000	CE	CE	CE	SG	SG
	7,000	CE	CE	CE	SG	SG
	9,000	CE	CE	CE	DN	SG
Medium pipe crossing	1,000	DN	DN	DN	DN	DN
	3,000	SG	SG	SG	SG	DN
	5,000	SG	SG	SG	SG	SG
	7,000	SG	SG	SG	SG	DN
	9,000	SG	SG	DN	SG	DN
Medium box crossing	1,000	DN	DN	DN	DN	DN
	3,000	SG	SG	SG	SG	DN
	5,000	SG	SG	SG	SG	SG
	7,000	SG	SG	SG	SG	DN
	9,000	SG	SG	DN	SG	DN
Large box crossing	1,000	DN	DN	DN	DN	DN
	3,000	SG	SG	DN	DN	DN
	5,000	SG	SG	DN	SG	DN
	7,000	SG	DN	DN	DN	DN
	9,000	DN	DN	DN	DN	DN

Note: CE – Culvert Extension, DN – Do Nothing, SG – Safety Grates

The 34 ft offset (outside clear zone) models only include the first three alternatives as the culvert was assumed to be located outside the clear zone.

For the small pipe culvert, culvert extension was the most preferable alternative when the distance between the edge of the traveled way and the culvert end is less than 20 ft for all ranges of traffic volumes (except for AADT less than 1,000 vpd for a 20 ft offset). As the culvert offset increased beyond 20 ft for small pipe, the best alternative changed from culvert extension to either installing safety grates or do nothing. This is because as the offset increases, the length to extend the culvert would also increase, which would result in higher installation costs compared to other alternatives.

The best alternative for both medium pipe culvert and medium box culvert for all ranges of AADT and offsets are similar to those shown in Table 16. The primary reason for this trend is that in the analysis of RSAP, the only difference between these two types of culvert is the culvert installation costs, as shown in Table 9. Other variables, such as the width/diameter of the culvert, safety grate costs (Table 12), and guardrail costs, remain the same. Thus, the benefit-cost ratio did not change significantly. For these two types of culverts, the majority of the cases suggest that installing safety grates would be more effective compared to other alternatives (except for cases with an AADT less than 1,000 vpd and culvert outside the clear zone).

For large box culverts, Table 16 shows that, in most cases, the do-nothing alternative is preferable. This result is obtained because the installation cost for safety grates is significantly higher for this type of culvert compared to others. Similarly, for culvert extensions, the cost for installing large box culverts is higher compared to medium box culverts and small and medium pipe culverts.

The benefit-cost ratios for installing guardrails was negative in all cases, indicating that the crash costs associated with the guardrails were always higher than the other alternatives. The findings suggested that, while the guardrail may reduce the probability of vehicles striking the culvert resulting in serious injury, it would in return increase the probability of vehicles being involved in PDO crashes due to the presence of a guardrail.

6.2.2 RSAP Scenario 2: Four-Lane 70 MPH Divided Highways

Table 17 shows the RSAP results for four-lane 70 mph divided highways.

Table 17. Best case alternatives for four-lane 70 mph divided highways

		Offset (feet)				
Culvert type	**AADT**	**14.0**	**19.0**	**24.0**	**29.0**	**34.0**
Small pipe crossing	10,000	CE	SG	SG	SG	DN
	20,000	CE	SG	SG	SG	SG
	30,000	CE	SG	SG	SG	SG
	40,000	CE	SG	SG	SG	SG
	50,000	CE	CE	SG	SG	SG
Medium pipe crossing	10,000	SG	SG	SG	DN	DN
	20,000	SG	SG	SG	SG	SG
	30,000	SG	SG	SG	SG	SG
	40,000	SG	SG	SG	SG	SG
	50,000	SG	SG	SG	SG	SG
Medium box crossing	10,000	SG	SG	SG	DN	DN
	20,000	SG	SG	SG	SG	SG
	30,000	SG	SG	SG	SG	SG
	40,000	SG	SG	SG	SG	SG
	50,000	SG	SG	SG	SG	SG
Large box crossing	10,000	SG	SG	DN	DN	DN
	20,000	SG	SG	SG	DN	DN
	30,000	SG	SG	SG	DN	DN
	40,000	SG	SG	SG	DN	DN
	50,000	SG	SG	SG	SG	SG
Small pipe median	10,000	CE	SG	SG	SG	DN
	20,000	CE	SG	SG	SG	SG
	30,000	CE	SG	SG	SG	SG
	40,000	CE	SG	SG	SG	SG
	50,000	CE	CE	SG	SG	SG

Note: CE – Culvert Extension, DN – Do Nothing, SE – Safety Grates

Only small pipe culverts were modeled in RSAP for median culverts because these were the only culverts that were seen to be present in the culvert database. Similar to two-lane undivided highways, cases with offset outside the clear zone had only the first three alternatives.

For small pipe crossing culverts, culvert extension was observed to be the optimal choice when the offset value is less than 14 ft for all ranges of traffic volumes. As the culvert offset increase beyond 14 ft, the installation of safety grates was shown to be more economical when compared to other alternatives due to the low installation cost. Note that for traffic volumes less than 10,000 vpd, if the culvert was located outside the clear zone, none of the safety treatments proved to be cost-effective.

Similar to the two-lane undivided highway analyses, both medium pipe crossing culverts and medium box crossing culverts had the same trend for all cases. As mentioned previously, the only difference between these two types of culverts is the cost of installation where medium box culvert is twice the cost of medium pipe culvert. Table 17 suggests that these two types of culverts would have to most economic benefits when safety grates is used when AADT is greater than 20,000 vpd.

For large box crossing culverts, Table 17 shows that safety grates was preferred the most when the culvert offset is less than 24 ft except for AADT less than 10,000 vpd. This safety treatment was preferred mainly because of the lower installation cost compared to other treatments. However, as the culvert offset increase beyond 29 ft for AADT less than 40,000 vpd, none of the safety treatments showed positive impacts in terms of economic benefits.

For small pipe median culverts, the same trend was observed from the small pipe crossing culvert case. Culvert extension was preferred when the culvert offset is less than 14 ft. As the distance between the edge of the travelled way and the culvert end increases, safety grates become more preferable as compared to other alternatives.

6.2.3 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 with a VSL of $4.5 million.

The cost of installation of safety grates, guardrail, and culvert extensions for this scenario were $4000, $14,540, and $21,191, respectively. 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:

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

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 annualization, these costs came out to be $294, $1,231, and $2,018, 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 18 provides the details of different costs from the Iowa DOT and RSAP results.

Table 18. 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	$3,340
Safety grates installed (Alt 2)	$294	$800	$2	$2,008
Guardrail installed (Alt 3)	$1,231	$1,600	$164	$6,697
Culvert extension (Alt 4)	$2,018	$600	$0	$2,194

A proper detailed summary of costs, crash, and injury information can help in a reliable estimation of benefit-cost analyses (Alluri et al. 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.

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

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

$$BCR_{21} = \frac{CC_1 - CC_2}{(I_2+M_2+R_2)-(I_1+M_1+R_1)} = \frac{3340-2008}{(294+800+2)-(0+600+0)} = 2.69 \quad (8)$$

This implies that installing safety grates will give a BCR of 2.69, as compared to the do-nothing approach. Therefore, installing a culvert grate is cost beneficial. Now, the other alternatives will be compared to the safety grates installed approach. The incremental BCR for installing guardrails as compared to safety grates is calculated as:

$$BCR_{32} = \frac{CC_2 - CC_3}{(I_3+M_3+R_3)-(I_2+M_2+R_2)} = \frac{2008-6697}{(1231+1600+164)-(294+800+2)} = -2.47 \quad (9)$$

This BCR 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 the 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 BCR for culvert extension as compared to safety grates is calculated as:

$$BCR_{42} = \frac{CC_2 - CC_4}{(I_4+M_4+R_4)-(I_2+M_2+R_2)} = \frac{2008-2194}{(2018+600+0)-(294+800+2)} = -0.12 \quad (10)$$

The BCR for this alternative is also negative, as compared to safety grates. Since guardrail installation and culvert extension both showed a negative BCR as compared to safety grates and safety grates showed a positive BCR as compared to the base approach of leaving the culvert unprotected, safety grates would be justified as the most optimal alternative. Table 19 shows the final benefit-cost ratios matrix as calculated using RSAP.

Table 19. Benefit-cost ratios matrix between different alternatives

VSL $6.2 million				
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
Alt. 1	1.00	2.69	-1.40	0.57
Alt. 2		0.00	-2.47	-0.12
Alt. 3			0.00	-11.96
Alt. 4				0.00

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row; cells are blank whenever that comparison would be redundant

7. CONCLUSIONS

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 crashes 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.

An extensive literature review was conducted to identify potential safety treatments for protecting errant vehicles from striking the 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, 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.

The research team conducted an in-depth evaluation of the existing culvert database provided by the Iowa DOT. Subsequently, the 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 furthest 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 data set 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.

Given concerns related to the spatial accuracy of crash data with respect to culvert locations, as well as concerns with respect to the underreporting of culvert-involved crashes, the second stage of the analysis involved the use of 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 installation and maintenance costs were obtained from the Iowa DOT and several online resources. A total of 225 different models were designed in RSAP based on the highway system, culvert sizes, different AADT, and culvert offsets.

Ultimately, the results of this study suggest that the installation of safety grates on culvert openings provides a promising alternative for most of the 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, different types of culverts suggested the use of different treatments. For small pipe crossing culverts, culvert extension was preferred for offsets less than 20 ft, when compared to other alternatives. For medium pipe and box culverts, both displayed similar trends where the majority of the cases suggested that installing safety grates would be more effective as opposed to other treatments or the base case. As for large box culverts, most of the cases preferred the base case (do nothing) when the culvert offset is beyond 14 ft.

On four-lane 70 mph divided highways, the majority of cases suggested that safety grates were the most cost-effective treatment compared to other alternatives. The analysis of this facility type showed that safety grates were also preferable for small pipe crossing culverts and small pipe median culverts for all cases. The same was true for medium pipe crossing culverts and medium box crossing culverts.

In cases where extension of culverts outside the clear zone was defined, the results showed that the BCR was positive; however, this was always less than the BCR 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 BCRs for the installation of guardrails near the edge of the travel lanes were consistently negative, mainly because of the increase in crash costs and high installation and maintenance costs compared to the other alternatives. 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 were likely numerous cases where a crash occurred with a culvert but 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. Generally, these unreported crashes tend to be less severe and, as such, the number of crashes predicted under various scenarios using RSAP is higher than what was shown by the in-service evaluation.

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 in 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 data set having the accurate installation and maintenance costs with varying sizes for culverts and safety grates, it would 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. For such crashes, it would 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-1-1. BCRs for small pipe culverts at 1,000 and 3,000 vpd

Small Pipe Culvert – 1,000 vpd – 8 ft					**Small Pipe Culvert – 3,000 vpd – 8 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.41	3.58	-0.25	**Alt 1**	1.00	4.56	6.80	-0.48
Alt 2		0.00	4.43	-0.76	**Alt 2**		0.00	8.42	-1.41
Alt 4			0.00	-2.6	**Alt 4**			0.00	-4.82
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 1,000 vpd - 14 ft					**Small Pipe Culvert – 3,000 vpd – 14 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	1.84	2.52	-0.39	**Alt 1**	1.00	3.49	4.78	-0.74
Alt 2		0.00	3.00	-0.78	**Alt 2**		0.00	5.71	-1.45
Alt 4			0.00	-2.00	**Alt 4**			0.00	-3.64
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 1,000 vpd – 20 ft					**Small Pipe Culvert – 3,000 vpd – 20 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	1.43	1.64	-0.68	**Alt 1**	1.00	2.70	3.12	-1.23
Alt 2		0.00	1.8	-1.02	**Alt 2**		0.00	3.42	-1.82
Alt 4			0.00	1.83	**Alt 4**			0.00	-3.19
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 1,000 vpd – 26 ft					**Small Pipe Culvert – 3,000 vpd – 26 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	1.31	0.93	-0.86	**Alt 1**	1.00	2.48	1.76	-1.59
Alt 2		0.00	0.66	-1.21	**Alt 2**		0.00	1.25	-2.18
Alt 4			0.00	-1.73	**Alt 4**			0.00	-3.03
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 1,000 vpd - 32 ft					**Small Pipe Culvert – 3,000 vpd - 32 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.46	-0.95		**Alt 1**	1.00	2.77	-1.78	
Alt 2		0.00	-1.33		**Alt 2**		0.00	-2.42	
Alt 3			0.00		**Alt 3**			0.00	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row

Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table A-1-2. BCRs for small pipe culverts at 5,000 and 7,000 vpd

Small Pipe Culvert – 5,000 vpd – 8 ft					Small Pipe Culvert – 7,000 vpd – 8 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	4.80	7.16	-0.50	**Alt 1**	1.00	4.23	6.31	-0.45
Alt 2		0.00	8.86	-1.48	**Alt 2**		0.00	7.81	-1.31
Alt 4			0.00	-5.06	**Alt 4**			0.00	-4.38
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 5,000 vpd – 14 ft					**Small Pipe Culvert – 7,000 vpd – 14 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	3.67	5.03	-0.77	**Alt 1**	1.00	3.24	4.44	-0.70
Alt 2		0.00	6.01	-1.52	**Alt 2**		0.00	5.29	-1.34
Alt 4			0.00	-3.82	**Alt 4**			0.00	-3.25
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 5,000 vpd – 20 ft					**Small Pipe Culvert – 7,000 vpd – 20 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.84	3.28	-1.29	**Alt 1**	1.00	2.51	2.89	-1.15
Alt 2		0.00	3.60	-1.91	**Alt 2**		0.00	3.17	-1.65
Alt 4			0.00	-3.34	**Alt 4**			0.00	-2.77
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 5,000 vpd – 26 ft					**Small Pipe Culvert – 7,000 vpd – 26 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.61	1.86	-1.67	**Alt 1**	1.00	2.30	1.64	-1.47
Alt 2		0.00	1.32	-2.28	**Alt 2**		0.00	1.16	-1.96
Alt 4			0.00	-3.17	**Alt 4**			0.00	-2.65
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert – 5,000 vpd – 32 ft					**Small Pipe Culvert – 7,000 vpd – 32 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.91	-1.86		**Alt 1**	1.00	2.57	-1.71	
Alt 2		0.00	-2.53		**Alt 2**		0.00	-2.26	
Alt 3			0.00		**Alt 3**			0.00	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row

Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table A-1-3. BCRs for small pipe culverts at 9,000 vpd

Small Pipe Culvert – 9,000 vpd – 8 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	3.43	5.11	-0.37
Alt 2		0.00	6.32	-1.07
Alt 4			0.00	-3.58
Alt 3				0.00
Small Pipe Culvert – 9,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.63	3.59	-0.58
Alt 2		0.00	4.29	-1.10
Alt 4			0.00	-2.67
Alt 3				0.00
Small Pipe Culvert – 9,000 vpd – 20 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.03	2.34	-0.94
Alt 2		0.00	2.57	-1.35
Alt 4			0.00	-2.29
Alt 3				0.00
Small Pipe Culvert – 9,000 vpd – 26 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	1.87	1.33	-1.21
Alt 2		0.00	0.94	-1.61
Alt 4			0.00	-2.19
Alt 3				0.00
Small Pipe Culvert – 9,000 vpd – 32 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.08	-1.41	
Alt 2		0.00	-1.86	
Alt 3			0.00	

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Table A-2-1. BCRs for medium pipe culverts at 1,000 and 3,000 vpd

Medium Pipe Culvert – 1,000 vpd – 8 ft					Medium Pipe Culvert – 3,000 vpd – 8 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.87	-0.19	1.21	**Alt 1**	1.00	3.55	-0.36	2.30
Alt 2		0.00	-1.01	1.00	**Alt 2**		0.00	-1.88	1.89
Alt 3			0.00	10.05	**Alt 3**			0.00	21.19
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 1,000 vpd – 14 ft					**Medium Pipe Culvert – 3,000 vpd – 14 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.63	-0.34	0.86	**Alt 1**	1.00	3.08	-0.62	1.64
Alt 2		0.00	-1.05	0.62	**Alt 2**		0.00	-1.92	1.17
Alt 3			0.00	14.87	**Alt 3**			0.00	43.35
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 1,000 vpd – 20 ft					**Medium Pipe Culvert – 3,000 vpd – 20 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.16	-0.63	0.55	**Alt 1**	1.00	2.20	-1.17	1.05
Alt 2		0.00	-1.23	0.36	**Alt 2**		0.00	-2.19	0.68
Alt 3			0.00	68.83	**Alt 3**			0.00	-43.33
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 1,000 vpd – 26 ft					**Medium Pipe Culvert – 3,000 vpd – 26 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.53	-0.84	0.32	**Alt 1**	1.00	2.89	-1.52	0.61
Alt 2		0.00	-1.61	-0.07	**Alt 2**		0.00	-2.81	-0.13
Alt 3			0.00	-329.25	**Alt 3**			0.00	-24.97
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 1,000 vpd – 32 ft					**Medium Pipe Culvert – 3,000 vpd – 32 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.02	-0.93		**Alt 1**	1.00	1.93	-1.77	
Alt 2		0.00	-1.56		**Alt 2**		0.00	-2.82	
Alt 3			0.00		**Alt 3**			0.00	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row

Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table A-2-2. BCRs for medium pipe culverts at 5,000 and 7,000 vpd

Medium Pipe Culvert – 5,000 vpd – 8 ft					Medium Pipe Culvert – 7,000 vpd – 8 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.73	-0.37	2.42	**Alt 1**	1.00	3.29	-0.35	2.13
Alt 2		0.00	-1.96	1.99	**Alt 2**		0.00	-1.73	1.76
Alt 4			0.00	22.48	**Alt 3**			0.00	22.79
Alt 3				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 5,000 vpd – 14 ft					**Medium Pipe Culvert – 7,000 vpd – 14 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.24	-0.65	1.72	**Alt 1**	1.00	2.86	-0.60	1.52
Alt 2		0.00	-2.01	1.23	**Alt 2**		0.00	-1.74	1.08
Alt 4			0.00	47.66	**Alt 3**			0.00	172.84
Alt 3				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 5,000 vpd – 20 ft					**Medium Pipe Culvert – 7,000 vpd – 20 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.32	-1.23	1.11	**Alt 1**	1.00	2.04	-1.09	0.97
Alt 2		0.00	-2.30	0.71	**Alt 2**		0.00	-1.95	0.63
Alt 3			0.00	-43.00	**Alt 3**			0.00	-15.73
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 5,000 vpd – 26 ft					**Medium Pipe Culvert – 7,000 vpd – 26 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.04	-1.60	0.64	**Alt 1**	1.00	2.69	-1.40	0.57
Alt 2		0.00	-2.94	-0.14	**Alt 2**		0.00	-2.47	-0.12
Alt 3			0.00	-25.28	**Alt 3**			0.00	-11.96
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 5000 vpd – 32 ft					**Medium Pipe Culvert – 7000 vpd – 32 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.03	-1.85		**Alt 1**	1.00	1.79	-1.7	
Alt 2		0.00	-2.96		**Alt 2**		0.00	-2.58	
Alt 3			0.00		**Alt 3**			0.00	

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Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table A-2-3. BCRs for medium pipe culverts at 9,000 vpd

Medium Pipe Culvert – 9,000 vpd – 8 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.67	-0.28	1.73
Alt 2		0.00	-1.41	1.42
Alt 3			0.00	17.54
Alt 4				0.00
Medium Pipe Culvert – 9,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.32	-0.49	1.23
Alt 2		0.00	-1.43	0.88
Alt 3			0.00	81.62
Alt 4				0.00
Medium Pipe Culvert – 9,000 vpd – 20 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.66	-0.90	0.79
Alt 2		0.00	-1.61	0.51
Alt 3			0.00	-14.13
Alt 4				0.00
Medium Pipe Culvert – 9,000 vpd – 26 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.18	-1.15	0.46
Alt 2		0.00	-2.03	-0.1
Alt 3			0.00	-10.56
Alt 4				0.00
Medium Pipe Culvert – 9,000 vpd – 32 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.45	-1.39	
Alt 2		0.00	-2.13	
Alt 3			0.00	

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Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table A-3-1. BCRs for medium box culverts at 1,000 and 3,000 vpd

Medium Box Culvert – 1,000 vpd – 8 ft					**Medium Box Culvert – 3,000 vpd – 8 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.87	-0.19	0.58	**Alt 1**	1.00	3.55	-0.36	1.1
Alt 2		0.00	-1.01	0.41	**Alt 2**		0.00	-1.88	0.77
Alt 3			0.00	1.12	**Alt 3**			0.00	2.15
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 1,000 vpd – 14 ft					**Medium Box Culvert – 3,000 vpd – 14 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.63	-0.34	0.41	**Alt 1**	1.00	3.08	-0.62	0.78
Alt 2		0.00	-1.05	0.25	**Alt 2**		0.00	-1.92	0.48
Alt 3			0.00	1.00	**Alt 3**			0.00	1.95
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 1,000 vpd – 20 ft					**Medium Box Culvert – 3,000 vpd – 20 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.16	-0.63	0.26	**Alt 1**	1.00	2.20	-1.17	0.5
Alt 2		0.00	-1.23	0.15	**Alt 2**		0.00	-2.19	0.28
Alt 3			0.00	1.06	**Alt 3**			0.00	2.2
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 1,000 vpd – 26 ft					**Medium Box Culvert – 3,000 vpd – 26 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.53	-0.84	0.15	**Alt 1**	1.00	2.89	-1.52	0.29
Alt 2		0.00	-1.61	-0.03	**Alt 2**		0.00	-2.81	-0.05
Alt 3			0.00	1.07	**Alt 3**			0.00	2.27
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 1,000 vpd – 32 ft					**Medium Box Culvert – 3,000 vpd – 32 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 4**	
Alt 1	1.00	1.02	-0.93		**Alt 1**	1.00	1.93	-1.77	
Alt 2		0.00	-1.56		**Alt 2**		0.00	-2.82	
Alt 3			0.00		**Alt 4**			0.00	

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Table A-3-2. BCRs for medium box culverts at 5,000 and 7,000 vpd

Medium Box Culvert – 5,000 vpd – 8 ft					Medium Box Culvert – 7,000 vpd – 8 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.73	-0.37	1.16	**Alt 1**	1.00	3.29	-0.35	1.02
Alt 2		0.00	-1.96	0.82	**Alt 2**		0.00	-1.73	0.72
Alt 3			0.00	2.26	**Alt 3**			0.00	2.04
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 5,000 vpd – 14 ft					**Medium Box Culvert – 7,000 vpd – 14 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.24	-0.65	0.82	**Alt 1**	1.00	2.86	-0.60	0.73
Alt 2		0.00	-2.01	0.5	**Alt 2**		0.00	-1.74	0.44
Alt 3			0.00	2.06	**Alt 3**			0.00	1.91
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 5,000 vpd – 20 ft					**Medium Box Culvert – 7,000 vpd – 20 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.32	-1.23	0.53	**Alt 1**	1.00	2.04	-1.09	0.47
Alt 2		0.00	-2.30	0.29	**Alt 2**		0.00	-1.95	0.26
Alt 3			0.00	2.32	**Alt 3**			0.00	2.34
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 5,000 vpd – 26 ft					**Medium Box Culvert – 7,000 vpd – 26 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.04	-1.60	0.31	**Alt 1**	1.00	2.69	-1.40	0.27
Alt 2		0.00	-2.94	-0.06	**Alt 2**		0.00	-2.47	-0.05
Alt 3			0.00	2.4	**Alt 3**			0.00	2.47
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 5,000 vpd – 32 ft					**Medium Box Culvert – 7,000 vpd – 32 ft**				
	Alt 1	**Alt 2**	**Alt 4**			**Alt 1**	**Alt 2**	**Alt 4**	
Alt 1	1.00	2.03	-1.85		**Alt 1**	1.00	1.79	-1.7	
Alt 2		0.00	-2.96		**Alt 2**		0.00	-2.58	
Alt 4			0.00		**Alt 4**			0.00	

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Table A-3-3. BCRs for medium box culverts at 9,000 vpd

Medium Box Culvert – 9,000 vpd – 8 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.67	-0.28	0.83
Alt 2		0.00	-1.41	0.58
Alt 3			0.00	1.65
Alt 4				0.00
Medium Box Culvert – 9,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.32	-0.49	0.59
Alt 2		0.00	-1.43	0.36
Alt 3			0.00	1.54
Alt 4				0.00
Medium Box Culvert – 9,000 vpd – 20 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.66	-0.90	0.38
Alt 2		0.00	-1.61	0.21
Alt 3			0.00	1.87
Alt 4				0.00
Medium Box Culvert – 9,000 vpd – 26 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.18	-1.15	0.22
Alt 2		0.00	-2.03	-0.04
Alt 3			0.00	1.97
Alt 4				0.00
Medium Box Culvert – 9,000 vpd – 32 ft				
	Alt 1	**Alt 2**	**Alt 4**	
Alt 1	1.00	1.45	-1.39	
Alt 2		0.00	-2.13	
Alt 4			0.00	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row

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Table A-4-1. BCRs for large box culverts at 1,000 and 3,000 vpd

Large Box Culvert – 1,000 vpd – 8 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	-0.07	1.31	0.45
Alt 3		0.00	-2.19	0.68
Alt 2			0.00	0.26
Alt 4				0.00

Large Box Culvert – 3,000 vpd – 8 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	-0.13	2.49	0.86
Alt 3		0.00	-4.00	1.29
Alt 2			0.00	0.49
Alt 4				0.00

Large Box Culvert – 1,000 vpd – 14 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	-0.24	1.09	0.32
Alt 3		0.00	-1.99	0.58
Alt 2			0.00	0.14
Alt 4				0.00

Large Box Culvert – 3,000 vpd – 14 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	-0.46	2.06	0.60
Alt 3		0.00	-3.55	1.12
Alt 2			0.00	0.27
Alt 4				0.00

Large Box Culvert – 1,000 vpd – 20 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	0.86	-0.57	0.20
Alt 2		0.00	-2.19	0.06
Alt 3			0.00	0.61
Alt 4				0.00

Large Box Culvert – 3,000 vpd – 20 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.63	-1.03	0.39
Alt 2		0.00	-3.66	0.11
Alt 3			0.00	1.21
Alt 4				0.00

Large Box Culvert – 1,000 vpd – 26 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.03	-0.82	0.11
Alt 2		0.00	-2.82	-0.09
Alt 3			0.00	0.62
Alt 4				0.00

Large Box Culvert – 3,000 vpd – 26 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.95	-1.44	0.22
Alt 2		0.00	-4.57	-0.17
Alt 3			0.00	1.23
Alt 4				0.00

Large Box Culvert – 1,000 vpd – 32 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	0.39	-0.91	
Alt 2		0.00	-2.32	
Alt 3			0.00	

Large Box Culvert – 3,000 vpd – 32 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	0.74	-1.64	
Alt 2		0.00	-3.77	
Alt 3			0.00	

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Table A-4-2. BCRs for large box culverts at 5,000 and 7,000 vpd

Large Box Culvert – 5,000 vpd – 8 ft					**Large Box Culvert – 7,000 vpd – 8 ft**				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**		**Alt 1**	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	-0.14	2.62	0.90	**Alt 1**	1.00	-0.14	2.31	0.79
Alt 3		0.00	-4.19	1.36	**Alt 3**		0.00	-3.59	1.22
Alt 2			0.00	0.52	**Alt 2**			0.00	0.46
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 5,000 vpd – 14 ft					**Large Box Culvert – 7,000 vpd – 14 ft**				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	-0.48	2.17	0.63	**Alt 1**	1.00	1.91	-0.45	0.56
Alt 3		0.00	-3.72	1.18	**Alt 2**		0.00	-3.12	0.25
Alt 2			0.00	0.29	**Alt 3**			0.00	1.09
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 5,000 vpd – 20 ft					**Large Box Culvert – 7,000 vpd – 20 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.72	-1.08	0.41	**Alt 1**	1.00	1.52	-0.98	0.36
Alt 2		0.00	-3.83	0.11	**Alt 2**		0.00	-3.09	0.10
Alt 3			0.00	1.28	**Alt 3**			0.00	1.24
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 5,000 vpd – 26 ft					**Large Box Culvert – 7,000 vpd – 26 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.06	-1.51	0.23	**Alt 1**	1.00	1.81	-1.34	0.20
Alt 2		0.00	-4.78	-0.18	**Alt 2**		0.00	-3.83	-0.16
Alt 3			0.00	1.30	**Alt 3**			0.00	1.28
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 5,000 vpd – 32 ft					**Large Box Culvert – 7,000 vpd – 32 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	0.78	-1.79		**Alt 1**	1.00	0.68	-1.66	
Alt 2		0.00	-4.08		**Alt 2**		0.00	-3.43	
Alt 3			0.00		**Alt 3**			0	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row

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Table A-4-3. BCRs for large box culverts at 9,000 vpd

Large Box Culvert – 9,000 vpd – 8 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	-0.11	1.87	0.64
Alt 3		0.00	-2.96	0.98
Alt 2			0.00	0.37
Alt 4				0.00
Large Box Culvert – 9,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.55	-0.37	0.45
Alt 2		0.00	-2.57	0.20
Alt 3			0.00	0.88
Alt 4				0.00
Large Box Culvert – 9,000 vpd – 20 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.23	-0.80	0.29
Alt 2		0.00	-2.56	0.08
Alt 3			0.00	1.00
Alt 4				0.00
Large Box Culvert – 9,000 vpd – 26 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.47	-1.10	0.16
Alt 2		0.00	-3.18	-0.13
Alt 3			0.00	1.03
Alt 4				0.00
Large Box Culvert – 9,000 vpd – 32 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	0.55	-1.36	
Alt 2		0.00	-2.85	
Alt 3			0.00	

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APPENDIX B. BENEFIT-COST RATIOS MATRIX FOR FOUR-LANE 70 MPH DIVIDED HIGHWAYS

Table B-1-1. BCRs for small pipe culverts at 10,000 and 20,000 vpd

Small Pipe Culvert – 10,000 vpd – 14 ft					Small Pipe Culvert – 20,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	6.42	-0.12	3.49	**Alt 1**	1.00	8.11	-0.15	4.41
Alt 2		0.00	-1.52	2.65	**Alt 2**		0.00	-1.90	3.35
Alt 3			0.00	-13.72	**Alt 3**			0.00	-16.95
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 10,000 vpd – 19 ft					**Small Pipe Culvert – 20,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	4.80	-1.29	2.19	**Alt 1**	1.00	6.06	-1.62	2.77
Alt 2		0.00	-2.31	1.44	**Alt 2**		0.00	-2.88	1.83
Alt 3			0.00	-7.60	**Alt 3**			0.00	-9.32
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 10,000 vpd – 24 ft					**Small Pipe Culvert – 20,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.28	-2.19	1.2	**Alt 1**	1.00	4.14	-2.73	1.52
Alt 2		0.00	-2.99	0.61	**Alt 2**		0.00	-3.72	0.77
Alt 3			0.00	-6.73	**Alt 3**			0.00	-8.24
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 10,000 vpd – 29 ft					**Small Pipe Culvert – 20,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.47	-2.73	0.51	**Alt 1**	1.00	3.12	-3.40	0.64
Alt 2		0.00	-3.42	-0.05	**Alt 2**		0.00	-4.25	-0.06
Alt 3			0.00	-6.37	**Alt 3**			0.00	-7.79
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 10,000 vpd – 34 ft					**Small Pipe Culvert – 20,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.91	-2.95		**Alt 1**	1.00	2.41	-3.67	
Alt 2		0.00	-3.56		**Alt 2**		0.00	-4.41	
Alt 3			0.00		**Alt 3**			0.00	

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Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table B-1-2. BCRs for small pipe culverts at 30,000 and 40,000 vpd

Small Pipe Culvert – 30,000 vpd – 14 ft					Small Pipe Culvert – 40,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	7.70	-0.15	4.18	**Alt 1**	1.00	7.79	-0.15	4.24
Alt 2		0.00	-1.81	3.18	**Alt 2**		0.00	-1.83	3.22
Alt 3			0.00	-16.17	**Alt 3**			0.00	-16.36
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 30,000 vpd – 19 ft					**Small Pipe Culvert – 40,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	5.75	-1.54	2.63	**Alt 1**	1.00	5.82	-1.56	2.66
Alt 2		0.00	-2.75	1.73	**Alt 2**		0.00	-2.78	1.76
Alt 3			0.00	-8.91	**Alt 3**			0.00	-9.01
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 30,000 vpd – 24 ft					**Small Pipe Culvert – 40,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.93	-2.60	1.44	**Alt 1**	1.00	3.98	-2.63	1.46
Alt 2		0.00	-3.54	0.73	**Alt 2**			-3.58	0.74
Alt 3			0.00	-7.88	**Alt 3**			0.00	-7.96
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 30,000 vpd – 29 ft					**Small Pipe Culvert – 40,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.96	-3.23	0.61	**Alt 1**	1.00	3.00	-3.27	0.62
Alt 2		0.00	-4.05	-0.06	**Alt 2**		0.00	-4.10	-0.06
Alt 3			0.00	-7.45	**Alt 3**			0.00	-7.53
Alt 4				0.00	**Alt 4**				0.00
Small Pipe Culvert – 30,000 vpd – 34 ft					**Small Pipe Culvert – 40,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.29	-3.50		**Alt 1**	1.00	2.32	-3.54	
Alt 2		0.00	-4.21		**Alt 2**		0.00	-4.26	
Alt 3			0.00		**Alt 3**			0	

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Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table B-1-3. BCRs for small pipe culverts at 50,000 vpd

Small Pipe Culvert – 50,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	9.73	-0.19	5.30
Alt 2		0.00	-2.28	4.03
Alt 3			0.00	-19.92
Alt 4				0.00
Small Pipe Culvert – 50,000 vpd – 19 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	7.26	-1.92	3.33
Alt 2		0.00	-3.42	2.20
Alt 3			0.00	-10.88
Alt 4				0.00
Small Pipe Culvert – 50,000 vpd – 24 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	4.97	-3.24	1.83
Alt 2		0.00	-4.40	0.93
Alt 3			0.00	-9.60
Alt 4				0.00
Small Pipe Culvert – 50,000 vpd – 29 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.74	-4.02	0.77
Alt 2		0.00	-5.02	-0.07
Alt 3			0.00	-9.07
Alt 4				0.00
Small Pipe Culvert – 50,000 vpd – 34 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.90	-4.34	
Alt 2		0.00	-5.21	
Alt 3			0.00	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row
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Table B-2-1. BCRs for medium pipe culverts at 10,000 and 20,000 vpd

Medium Pipe Culvert – 10,000 vpd – 14 ft					Medium Pipe Culvert – 20,000 vpd – 14 ft				
	Alt 1	Alt 2	Alt 3	Alt 4		Alt 1	Alt 2	Alt 3	Alt 4
Alt 1	1.00	5.44	0.12	1.21	Alt 1	1.00	6.86	0.15	1.53
Alt 2		0.00	-2.31	0.58	Alt 2		0.00	-2.90	0.73
Alt 3			0.00	1.99	Alt 3			0.00	2.52
Alt 4				0.00	Alt 4				0.00
Medium Pipe Culvert – 10,000 vpd – 19 ft					Medium Pipe Culvert – 20,000 vpd – 19 ft				
	Alt 1	Alt 2	Alt 3	Alt 4		Alt 1	Alt 2	Alt 3	Alt 4
Alt 1	1.00	3.75	-1.17	0.75	Alt 1	1.00	4.74	-1.46	0.95
Alt 2		0.00	-2.87	0.30	Alt 2		0.00	-3.58	0.38
Alt 3			0.00	2.73	Alt 3			0.00	3.49
Alt 4				0.00	Alt 4				0.00
Medium Pipe Culvert – 10,000 vpd – 24 ft					Medium Pipe Culvert – 20,000 vpd – 24 ft				
	Alt 1	Alt 2	Alt 3	Alt 4		Alt 1	Alt 2	Alt 3	Alt 4
Alt 1	1.00	2.97	-2.09	0.47	Alt 1	1.00	3.75	-2.61	0.53
Alt 2		0.00	-3.59	0.09	Alt 2		0.00	-4.46	0.05
Alt 3			0.00	3.89	Alt 3			0.00	4.88
Alt 4				0.00	Alt 4				0.00
Medium Pipe Culvert – 10,000 vpd – 29 ft					Medium Pipe Culvert – 20,000 vpd – 29 ft				
	Alt 1	Alt 2	Alt 3	Alt 4		Alt 1	Alt 2	Alt 3	Alt 4
Alt 1	1.00	1.96	-2.69	0.16	Alt 1	1.00	2.48	-3.35	0.2
Alt 2		0.00	-3.93	-0.11	Alt 2		0.00	-4.87	-0.14
Alt 3			0.00	4.76	Alt 3			0.00	6.18
Alt 4				0.00	Alt 4				0.00
Medium Pipe Culvert – 10,000 vpd – 34 ft					Medium Pipe Culvert – 20,000 vpd – 34 ft				
	Alt 1	Alt 2	Alt 3			Alt 1	Alt 2	Alt 3	
Alt 1	1.00	1.92	-2.86		Alt 1	1.00	2.43	-3.56	
Alt 2		0.00	-4.05		Alt 2		0.00	-5.01	
Alt 3			0.00		Alt 3			0.00	

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Table B-2-2. BCRs for medium pipe culverts at 30,000 and 40,000 vpd

Medium Pipe Culvert – 30,000 vpd – 14 ft					Medium Pipe Culvert – 40,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	6.52	0.15	1.46	**Alt 1**	1.00	6.60	0.15	1.47
Alt 2		0.00	-2.76	0.7	**Alt 2**		0.00	-2.79	0.70
Alt 3			0.00	2.39	**Alt 3**			0.00	2.42
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 30,000 vpd – 19 ft					**Medium Pipe Culvert – 40,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	4.50	-1.39	0.9	**Alt 1**	1.00	4.56	-1.41	0.91
Alt 2		0.00	-3.4	0.36	**Alt 2**		0.00	-3.45	0.36
Alt 3			0.00	3.31	**Alt 3**			0.00	3.35
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 30,000 vpd – 24 ft					**Medium Pipe Culvert – 40,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.56	-2.49	0.5	**Alt 1**	1.00	3.61	-2.52	0.51
Alt 2		0.00	-4.25	0.05	**Alt 2**		0.00	-4.3	0.05
Alt 3			0.00	4.61	**Alt 3**			0.00	4.67
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 30,000 vpd – 29 ft					**Medium Pipe Culvert – 40,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.35	-3.19	0.19	**Alt 1**	1.00	2.38	-3.23	0.19
Alt 2		0.00	-4.64	-0.14	**Alt 2**		0.00	-4.7	-0.14
Alt 3			0.00	5.82	**Alt 3**			0.00	5.91
Alt 4				0.00	**Alt 4**				0.00
Medium Pipe Culvert – 30,000 vpd – 34 ft					**Medium Pipe Culvert – 40,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.30	-3.39		**Alt 1**	1.00	2.33	-3.43	
Alt 2		0.00	-4.78		**Alt 2**		0.00	-4.84	
Alt 3			0.00		**Alt 3**			0	

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Table B-2-3. BCRs for medium pipe culverts at 50,000 vpd

Medium Pipe Culvert – 50,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	8.24	0.19	1.84
Alt 2		0.00	-3.46	0.88
Alt 3			0.00	3.04
Alt 4				0.00
Medium Pipe Culvert – 50,000 vpd – 19 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	5.69	-1.74	1.14
Alt 2		0.00	-4.24	0.45
Alt 3			0.00	4.25
Alt 4				0.00
Medium Pipe Culvert – 50,000 vpd – 24 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	4.50	-3.10	0.64
Alt 2		0.00	-5.26	0.06
Alt 3			0.00	5.97
Alt 4				0.00
Medium Pipe Culvert – 50,000 vpd – 29 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.98	-3.96	0.24
Alt 2		0.00	-5.74	-0.17
Alt 3			0.00	7.61
Alt 4				0.00
Medium Pipe Culvert – 50,000 vpd – 34 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.91	-4.21	
Alt 2		0.00	-5.91	
Alt 3			0.00	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row

Blacked out cells are for an alternative that is not considered for that specific scenario; in each scenario, Alternative 4 refers to the option where the culvert is extended to the limits of the clear zone, and this alternative is blacked out in instances where the culvert has already been extended to, or beyond, the clear zone distance

Table B-3-1. BCRs for medium box culverts at 10,000 and 20,000 vpd

Medium Box Culvert – 10,000 vpd – 14 ft					Medium Box Culvert – 20,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	5.44	0.12	0.58	**Alt 1**	1.00	6.87	0.15	0.73
Alt 2		0.00	-2.31	0.26	**Alt 2**		0.00	-2.90	0.33
Alt 3			0.00	0.69	**Alt 3**			0.00	0.88
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 10,000 vpd – 19 ft					**Medium Box Culvert – 20,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.75	-1.17	0.36	**Alt 1**	1.00	4.74	-1.46	0.45
Alt 2		0.00	-2.87	0.13	**Alt 2**		0.00	-3.58	0.17
Alt 3			0.00	0.85	**Alt 3**			0.00	1.08
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 10,000 vpd – 24 ft					**Medium Box Culvert – 20,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.97	-2.09	0.2	**Alt 1**	1.00	3.75	-2.61	0.25
Alt 2		0.00	-3.59	0.02	**Alt 2**		0.00	-4.46	0.02
Alt 3			0.00	1.07	**Alt 3**			0.00	1.36
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 10,000 vpd – 29 ft					**Medium Box Culvert – 20,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.96	-2.69	0.07	**Alt 1**	1.00	2.48	-3.35	0.09
Alt 2		0.00	-3.93	-0.05	**Alt 2**		0.00	-4.87	-0.06
Alt 3			0.00	1.23	**Alt 3**			0.00	1.57
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 10,000 vpd – 34 ft					**Medium Box Culvert – 20,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.92	-2.86		**Alt 1**	1.00	2.43	-3.56	
Alt 2		0.00	-4.05		**Alt 2**		0.00	-5.01	
Alt 3					**Alt 3**			0.00	

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Table B-3-2. BCRs for medium box culverts at 30,000 and 40,000 vpd

Medium Box Culvert – 30,000 vpd – 14 ft					Medium Box Culvert – 40,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	6.52	0.15	0.70	**Alt 1**	1.00	6.60	0.15	0.71
Alt 2		0.00	-2.76	0.31	**Alt 2**		0.00	-2.79	0.31
Alt 3			0.00	0.83	**Alt 3**			0.00	0.84
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 30,000 vpd – 19 ft					**Medium Box Culvert – 40,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	4.50	-1.39	0.43	**Alt 1**	1.00	4.56	-1.41	0.44
Alt 2		0.00	-3.40	0.16	**Alt 2**		0.00	-3.45	0.16
Alt 3			0.00	1.02	**Alt 3**			0.00	1.03
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 30,000 vpd – 24 ft					**Medium Box Culvert – 40,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.56	-2.49	0.24	**Alt 1**	1.00	3.61	-2.52	0.24
Alt 2		0.00	-4.25	0.02	**Alt 2**		0.00	-4.30	0.02
Alt 3			0.00	1.28	**Alt 3**			0.00	1.30
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 30,000 vpd – 29 ft					**Medium Box Culvert – 40,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.35	-3.19	0.09	**Alt 1**	1.00	2.38	-3.23	0.09
Alt 2		0.00	-4.64	-0.06	**Alt 2**		0.00	-4.70	-0.06
Alt 3			0.00	1.49	**Alt 3**			0.00	1.51
Alt 4				0.00	**Alt 4**				0.00
Medium Box Culvert – 30,000 vpd – 34 ft					**Medium Box Culvert – 40,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.30	-3.39		**Alt 1**	1.00	2.33	-3.43	
Alt 2		0.00	-4.78		**Alt 2**		0.00	-4.84	
Alt 3			0.00		**Alt 3**			0	

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Table B-3-3. BCRs for medium box culverts at 50,000 vpd

Medium Box Culvert – 50,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	8.24	0.19	0.88
Alt 2		0.00	-3.46	0.39
Alt 3			0.00	1.06
Alt 4				0.00
Medium Box Culvert – 50,000 vpd – 19 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	5.69	-1.74	0.54
Alt 2		0.00	-4.24	0.20
Alt 3			0.00	1.30
Alt 4				0.00
Medium Box Culvert – 50,000 vpd – 24 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	4.50	-3.10	0.31
Alt 2		0.00	-5.26	0.03
Alt 3			0.00	1.64
Alt 4				0.00
Medium Box Culvert – 50,000 vpd – 29 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.98	-3.96	0.11
Alt 2		0.00	-5.74	-0.08
Alt 3			0.00	1.90
Alt 4				0.00
Medium Box Culvert – 50,000 vpd – 34 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.91	-4.21	
Alt 2		0.00	-5.91	
Alt 3			0.00	

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Table B-4-1. BCRs for large box culverts at 10,000 and 20,000 vpd

Large Box Culvert – 10,000 vpd – 14 ft					Large Box Culvert – 20,000 vpd – 14 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**		**Alt 1**	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	0.45	3.58	0.46	**Alt 1**	1.00	0.56	4.53	0.58
Alt 3		0.00	-5.84	0.46	**Alt 3**		0.00	-7.27	0.58
Alt 2			0.00	0.12	**Alt 2**			0.00	0.16
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 10,000 vpd – 19 ft					**Large Box Culvert – 20,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.57	-0.93	0.29	**Alt 1**	1.00	3.25	-1.17	0.37
Alt 2		0.00	-5.15	0.05	**Alt 2**		0.00	-6.36	0.05
Alt 3			0.00	0.55	**Alt 3**			0.00	0.7
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 10,000 vpd – 24 ft					**Large Box Culvert – 20,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.86	-1.96	0.16	**Alt 1**	1.00	2.36	-2.45	0.2
Alt 2		0.00	-5.57	-0.02	**Alt 2**		0.00	-6.85	-0.03
Alt 3			0.00	0.69	**Alt 3**			0.00	0.87
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 10,000 vpd – 29 ft					**Large Box Culvert – 20,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.44	-2.54	0.07	**Alt 1**	1.00	1.82	-3.16	0.08
Alt 2		0.00	-5.79	-0.08	**Alt 2**		0.00	-7.12	-0.1
Alt 3			0.00	0.78	**Alt 3**			0.00	0.99
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 10,000 vpd – 34 ft					**Large Box Culvert – 20,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.53	-2.80		**Alt 1**	1.00	1.93	-3.48	
Alt 2		0.00	-6.00		**Alt 2**		0.00	-7.37	
Alt 3			0.00		**Alt 3**			0.00	

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Table B-4-2. BCRs for large box culverts at 30,000 and 40,000 vpd

Large Box Culvert – 30,000 vpd – 14 ft					Large Box Culvert – 40,000 vpd – 14 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**		**Alt 1**	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	0.54	4.30	0.55	**Alt 1**	1.00	0.54	4.35	0.56
Alt 3		0.00	-6.93	0.55	**Alt 3**		0.00	-7.01	0.56
Alt 2			0.00	0.15	**Alt 2**			0.00	0.15
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 30,000 vpd – 19 ft					**Large Box Culvert – 40,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.09	-1.11	0.35	**Alt 1**	1.00	3.13	-1.12	0.35
Alt 2		0.00	-6.07	0.05	**Alt 2**		0.00	-6.14	0.05
Alt 3			0.00	0.67	**Alt 3**			0.00	0.67
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 30,000 vpd – 24 ft					**Large Box Culvert – 40,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.24	-2.33	0.19	**Alt 1**	1.00	2.26	-2.36	0.19
Alt 2		0.00	-6.54	-0.03	**Alt 2**		0.00	-6.62	-0.03
Alt 3			0.00	0.83	**Alt 3**			0.00	0.84
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 30,000 vpd – 29 ft					**Large Box Culvert – 40,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**		**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	1.73	-3.01	0.08	**Alt 1**	1.00	1.75	-3.05	0.08
Alt 2		0.00	-6.8	-0.1	**Alt 2**		0.00	-6.88	-0.1
Alt 3			0.00	0.94	**Alt 3**			0.00	0.95
Alt 4				0.00	**Alt 4**				0.00
Large Box Culvert – 30,000 vpd – 34 ft					**Large Box Culvert – 40,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.83	-3.32		**Alt 1**	1.00	1.86	-3.36	
Alt 2		0.00	-7.04		**Alt 2**		0.00	-7.12	
Alt 3			0.00		**Alt 3**			0	

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Table B-4-3. BCRs for large box culverts at 50,000 vpd

Large Box Culvert – 50,000 vpd – 14 ft				
	Alt 1	**Alt 3**	**Alt 2**	**Alt 4**
Alt 1	1.00	0.67	5.44	0.7
Alt 3		0.00	-8.61	0.7
Alt 2			0.00	0.19
Alt 4				0.00
Large Box Culvert – 50,000 vpd – 19 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	3.90	-1.39	0.44
Alt 2		0.00	-7.47	0.07
Alt 3			0.00	0.84
Alt 4				0.00
Large Box Culvert – 50,000 vpd – 24 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.83	-2.90	0.24
Alt 2		0.00	-8.03	-0.04
Alt 3			0.00	1.05
Alt 4				0.00
Large Box Culvert – 50,000 vpd – 29 ft				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**
Alt 1	1.00	2.19	-3.74	0.1
Alt 2		0.00	-8.33	-0.12
Alt 3			0.00	1.2
Alt 4				0.00
Large Box Culvert – 50,000 vpd - 34 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.32	-4.12	
Alt 2		0.00	-8.61	
Alt 3			0.00	

Green shading=alternative that has the highest benefit-cost ratio as compared to the other alternatives; the value in each column compares that alternative to the alternative in the corresponding row

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Table B-5-1. BCRs for small pipe median culverts at 10,000 and 20,000 vpd

Small Pipe Culvert (Median) – 10,000 vpd – 14 ft					Small Pipe Culvert (Median) – 20,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	3.61	3.25	-5.13	**Alt 1**	1.00	4.56	4.11	-6.39
Alt 2		0.00	2.96	-6.17	**Alt 2**		0.00	3.75	-7.67
Alt 4			0.00	-7.77	**Alt 4**			0.00	-9.63
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 10,000 vpd – 19 ft					**Small Pipe Culvert (Median) – 20,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.73	2.06	-5.12	**Alt 1**	1.00	3.44	2.60	-6.36
Alt 2		0.00	1.52	-5.99	**Alt 2**		0.00	1.93	-7.44
Alt 4			0.00	-7.22	**Alt 4**			0.00	-8.92
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 10,000 vpd – 24 ft					**Small Pipe Culvert (Median) – 20,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.57	1.17	-5.23	**Alt 1**	1.00	3.25	1.48	-6.49
Alt 2		0.00	0.05	-6.07	**Alt 2**		0.00	0.06	-7.52
Alt 4			0.00	-7.02	**Alt 4**			0.00	-8.67
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 10,000 vpd – 29 ft					**Small Pipe Culvert (Median) – 20,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.21	0.53	-5.31	**Alt 1**	1.00	2.79	0.67	-6.58
Alt 2		0.00	-0.80	-6.10	**Alt 2**		0.00	-1.02	-7.55
Alt 4			0.00	-6.90	**Alt 4**			0.00	-8.52
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 10,000 vpd – 34 ft					**Small Pipe Culvert (Median) – 20,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	1.96	-5.33		**Alt 1**	1.00	2.47	-6.61	
Alt 2		0.00	-6.08		**Alt 2**		0.00	-7.53	
Alt 3			0.00		**Alt 3**			0.00	

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Table B-5-2. BCRs for small pipe median culverts at 30,000 and 40,000 vpd

Small Pipe Culvert (Median) – 30,000 vpd – 14 ft					Small Pipe Culvert (Median) – 40,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	4.33	3.90	-6.08	**Alt 1**	1.00	4.39	3.95	-6.16
Alt 2		0.00	3.56	-7.31	**Alt 2**		0.00	3.61	-7.40
Alt 4			0.00	-9.18	**Alt 4**			0.00	-9.29
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 30,000 vpd – 19 ft					**Small Pipe Culvert (Median) – 40,000 vpd – 19 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	3.27	2.47	-6.06	**Alt 1**	1.00	3.31	2.50	-6.13
Alt 2		0.00	1.83	-7.09	**Alt 2**		0.00	1.85	-7.17
Alt 4			0.00	-8.51	**Alt 4**			0.00	-8.61
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 30,000 vpd – 24 ft					**Small Pipe Culvert (Median) – 40,000 vpd – 24 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	3.08	1.40	-6.19	**Alt 1**	1.00	3.12	1.42	-6.26
Alt 2		0.00	0.05	-7.17	**Alt 2**		0.00	0.06	-7.26
Alt 4			0.00	-8.28	**Alt 4**			0.00	-8.37
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 30,000 vpd – 29 ft					**Small Pipe Culvert (Median) – 40,000 vpd – 29 ft**				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**		**Alt 1**	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	2.64	0.64	-6.28	**Alt 1**	1.00	2.68	0.65	-6.35
Alt 2		0.00	-0.96	-7.20	**Alt 2**		0.00	-0.98	-7.29
Alt 4			0.00	-8.13	**Alt 4**			0.00	-8.22
Alt 3				0.00	**Alt 3**				0.00
Small Pipe Culvert (Median) – 30,000 vpd – 34 ft					**Small Pipe Culvert (Median) – 40,000 vpd – 34 ft**				
	Alt 1	**Alt 2**	**Alt 3**			**Alt 1**	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.35	-6.30		**Alt 1**	1.00	2.38	-6.38	
Alt 2		0.00	-7.18		**Alt 2**		0.00	-7.27	
Alt 3			0.00		**Alt 3**			0	

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Table B-5-3. BCRs for small pipe median culverts at 50,000 vpd

Small Pipe Culvert (Median) – 50,000 vpd – 14 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	5.47	4.94	-7.56
Alt 2		0.00	4.51	-9.06
Alt 4			0.00	-11.34
Alt 3				0.00
Small Pipe Culvert (Median) – 50,000 vpd – 19 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	4.13	3.13	-7.52
Alt 2		0.00	2.32	-8.77
Alt 4			0.00	-10.49
Alt 3				0.00
Small Pipe Culvert (Median) – 50,000 vpd – 24 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	3.89	1.77	-7.67
Alt 2		0.00	0.07	-8.87
Alt 4			0.00	-10.20
Alt 3				0.00
Small Pipe Culvert (Median) – 50,000 vpd – 29 ft				
	Alt 1	**Alt 2**	**Alt 4**	**Alt 3**
Alt 1	1.00	3.34	0.81	-7.77
Alt 2		0.00	-1.22	-8.90
Alt 4			0.00	-10.01
Alt 3				0.00
Small Pipe Culvert (Median) – 50,000 vpd – 34 ft				
	Alt 1	**Alt 2**	**Alt 3**	
Alt 1	1.00	2.97	-7.80	
Alt 2		0.00	-8.88	
Alt 3			0.00	

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