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Synthesis: Bridge Deck Drains

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16. Abstract Bridge deck drains are an integral component of bridges helping in the removal of runoff. The debris carried by the runoff clog drains frequently. The objective of this project is to synthesize and evaluate existing bridge deck drains and provide recommendations for the design, construction, and maintenance of bridge deck drains. The research findings were obtained through an extensive literature review, fact-finding surveys, and structured follow-up interviews. A thorough literature review was conducted to obtain a detailed understanding of bridge deck drains' failures, designs, construction, and maintenance in Texas and other states. The findings of the literature review were used to develop two surveys. Responses were collected from 17 TxDOT districts and 21 states other than Texas. Based on the survey responses, structured follow-up interviews were conducted with individuals with extensive experience with bridge deck drains. In total, the research team conducted six detailed follow-up interviews. The interview participants were asked to provide detailed information on bridge deck drain designs, construction, and maintenance. To ensure the effective removal of runoff from bridge decks in Texas, the researchers recommended standardizing the design and detailing of bridge deck drains. They also recommended inspecting bridge deck drains at least once before rainy seasons.					
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EXECUTIVE SUMMARY

Bridge deck drainage is an integral component of the bridge system, helping fast and effective removal of runoff from bridges. Bridge deck drains are frequently clogged due to the debris carried by rainfall-runoff. Bridge deck drains that can operate with minimum maintenance are essential to improve the traffic operation, enhance safety, and minimize deterioration of bridge deck structures. Hence, a comprehensive synthesis of the current state of knowledge and practice for bridge deck drains is necessary to identify the best practices that can help improve their performance. The objective of this project is to synthesize and evaluate existing bridge deck drains and provide recommendations for the design, construction, and maintenance of bridge deck drains.

The research findings were obtained through an extensive literature review, fact-finding surveys, and structured follow-up interviews. A thorough literature review was conducted to obtain a detailed understanding of bridge deck drains' failures, designs, construction, and maintenance in Texas and other states. The findings of the literature review were used to develop two questionnaires, one for all TxDOT districts and another for all states other than Texas to capture the current state of practice for bridge deck drains. Responses were collected from 17 TxDOT districts, 21 states other than Texas, the District of Columbia, and Quebec, Canada. The TxDOT responses were collected from the districts of Abilene, Amarillo, Atlanta, Austin, Beaumont, Bryan, Dallas, El Paso, Fort Worth, Houston, Lufkin, Odessa, Paris, Pharr, San Angelo, San Antonio, and Tyler. Responses outside Texas were collected from the states of Colorado, Florida, Georgia, Iowa, Kansas, Louisiana, Maine, Michigan, Nebraska, New Hampshire, New Jersey, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Carolina, Virginia, and Washington. Based on the survey responses, structured follow-up interviews were conducted with individuals with extensive experience with bridge deck drains. In total, the research team conducted six detailed follow-up interviews. The interview participants were asked to provide detailed information on bridge deck drain designs, construction, and maintenance.

The information collected from literature, survey questionnaire, and interviews were analyzed to present recommendations for bridge deck drains in Texas. For example, some of the recommendations are summarized here:

- The design and detailing of closed bridge deck drains should be standardized. Detailed drawings eliminate difficulties that contractors and inspectors face on the job site.
- Embedded systems' designs should start early during bridge design if they could not be avoided. Design decisions for bridges and embedded drains are interdependent.
- Free-fall of runoff can be allowed when permissible (no facilities or waterways below). It is recommended to allow free-fall of runoff only if runoff is not contaminated and environmental policies do not restrict free-fall from a waterway below a bridge. If one lane exists below a bridge, free-fall can be restricted from the bridge on the section that passes through a lane below a bridge. Free-fall can be allowed again after the bridge crosses the roadway.
- The number of bends should be minimized. Since debris accumulates at bends, it is recommended to reduce the number of bends, use long radius elbows instead of short radius elbows, and provide a cleanout at each bend. It is recommended to use T-connections instead of 90° bends because they offer an extra side to be used as a cleanout.
- The drain section of the TxDOT bridge asset management system should be re-evaluated. Re-evaluation will ensure that adequate information about the conditions and performances of deck drains is collected to keep them performing well.
- The surrounding conditions of a bridge should be considered when choosing inlets. Bridges receive different amounts of debris and precipitation. Some bridges accommodate cyclists and pedestrians while others do not. It should be noted that inlet designs differ in debris handling efficiency, hydraulic efficiency, and bicycle safety.
- Each expansion joint should be provided with a fixed point. The expansion goes to the weakest joint when expansion joints are not provided with a fixed point. Downspouts could break if the expansion goes to the weakest joint.
- Drains should be installed precisely where they are designed to be located on all bridges. It is recommended to have detailed design documents set by designers instead of leaving many decisions to contractors.
- Bridge deck drains should be inspected at least once before each rainy season, especially on bridges with high amounts of debris. If needed, the drains should be immediately cleaned using proper methods. For example, vacuums and pressure washers can be used when drains are clogged; loose washing with a vacuum system can be used to remove debris and dirt; Roto-rooters can be used to remove objects from drains.

CHAPTER 1 - INTRODUCTION

Texas has the most extensive U.S. bridge inventory, operating and maintaining 54,338 bridges for public vehicular traffic (TxDOT, 2018). TxDOT spent \$79.2 million for on-system bridge maintenance in FY 2018 (TxDOT, 2018). Bridge deck drainage maintenance is one of the major contributors to the overall bridge maintenance cost (Vlček et al., 2012). The rainfall runoff carries debris that causes frequent clogging in bridge deck drains. Poor bridge drainage results in water standing on the bridge pavements. Standing water deteriorates bridge structures and significantly increases the cost of bridge deck maintenance (Hammonds and Holley, 1995; Brown et al., 2009). Water flow in bridge pavement threatens traffic safety by increasing the risk of hydroplaning for vehicular traffic (Young et al., 1993). Bridge deck drains that can operate with minimum maintenance are essential to improve the traffic operation, enhance safety, and minimize deterioration of bridge deck structures. However, the drain types that can be used in bridges are limited due to the restrictions imposed by bridge aesthetics, elevation, structural integrity, and maintenance requirements (Young et al., 1993; Qian et al., 2013). Hence, a comprehensive synthesis of the current state of knowledge and practice for bridge deck drains is necessary to identify the best practices that can help improve their performance. The objective of this project is to synthesize and evaluate existing bridge deck drains and provide recommendations for the design, construction, and maintenance of bridge deck drains.

This research aims to capture the best practices and recommendations for bridge deck drain design, construction, and maintenance. This technical report explains all the tasks performed to acquire the set of recommendations for bridge deck drains. The report is organized as follows:

Chapter 1 is this introductory chapter.

Chapter 2 is the literature review for bridge deck drains.

Chapter 3 contains this project's survey results.

Chapter 4 contains the summary of 6 interviews about bridge deck drains.

Chapter 5 contains a project summary and recommendations for bridge deck drains.

Appendix A contains the survey questionnaire distributed in Texas.

Appendix B contains the survey questionnaire distributed outside Texas.

Appendix C contains the survey invitation e-mail for TxDOT districts.

Appendix D contains the survey invitation e-mail for states other than Texas.

Appendix E contains the value of this synthesis.

CHAPTER 2 - LITERATURE REVIEW ON BRIDGE DECK DRAINS

2.1 Bridge Deck Drainage Systems

Bridge deck drainage is an integral component of the bridge system, helping fast and effective removal of runoff from bridges. Bridge deck drains are frequently clogged due to the debris carried by rainfall-runoff as shown in Figure 2.1



Figure 2.1 Clogging of bridge deck drain (FHWA, 2015; Zealand, 2011)

Frequent clogging of bridge deck drains increases maintenance costs and threatens vehicle safety by increasing the risk of hydroplaning. Also, the free-fall of rainfall-runoff from bridges can cause erosion beneath those bridges, threatening the stability of bridges' substructures. Hence, this literature review is performed to determine the most appropriate drain type, drainage configurations, deck drain inlets, pipe materials, and sizes that can fulfill the following criteria:

- Minimization of maintenance
- Aesthetics preservation
- Avoidance of hydroplaning
- Structural integrity
- Minimization of spread
- Bicycle safety

- Protection of water quality

Bridge deck drainage systems are classified into two types (FHWA, 2015; SCDOT, 2006):

1. Open deck drainage system; and
2. Closed deck drainage system

Open deck drainage systems are horizontal or vertical penetrations through the bridge structures. Horizontal penetrations are the drainage slots that are constructed as a part of the bridge barriers and curbs. Figure 2.2 (a) shows a schematic presentation of the horizontal penetration to remove rainfall runoff through a drainage slot in the bridge railing. Vertical penetrations are the drainage slots in a bridge deck. The pipe extends through the bridge deck and receives the runoff from a grate inlet or a scupper inlet. The vertical penetration comprising a scupper inlet and a drainage pipe is schematically shown in Figure 2.2 (b). The open deck drainage system allows the runoff contaminated with chemicals and chlorides to come in direct contact with the bridge structural components (NDOT, 2008). This may result in steel corrosion and concrete spalling in bridge decks (Young et al., 1993). The open drainage system allows free-fall of runoff; hence, it should be avoided on bridges where free-falling runoff can erode the earth slopes and foundation of the superstructures.

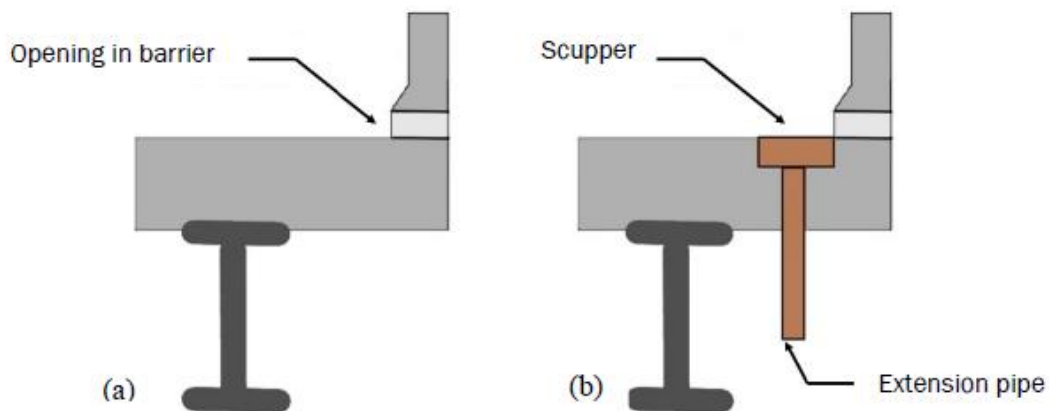


Figure 2.2 Open deck drainage system (a) Horizontal penetration (b) Vertical penetration

Closed deck drainage systems comprise grate inlets with a closed piping system affixed to bridge substructures for transporting runoff to a ground drainage inlet. Figure 2.3 shows a more detailed example of the closed deck drainage system used in bridges. Closed deck drainage systems are required when there are environmental concerns, such as contamination due to runoff, flooding, or soil erosion immediately below the bridge structure (SCDOT, 2006). Pipes in the closed deck drainage system are susceptible to corrosion and clogging due to the debris and sand carried by rainfall runoffs (SCDOT, 2006). The drainpipes that are embedded within a bridge structure are challenging to maintain through cleaning and flushing. The pipes running down the exterior of a bridge in a closed deck drainage system degrade the bridge aesthetics (Young et al., 1993).

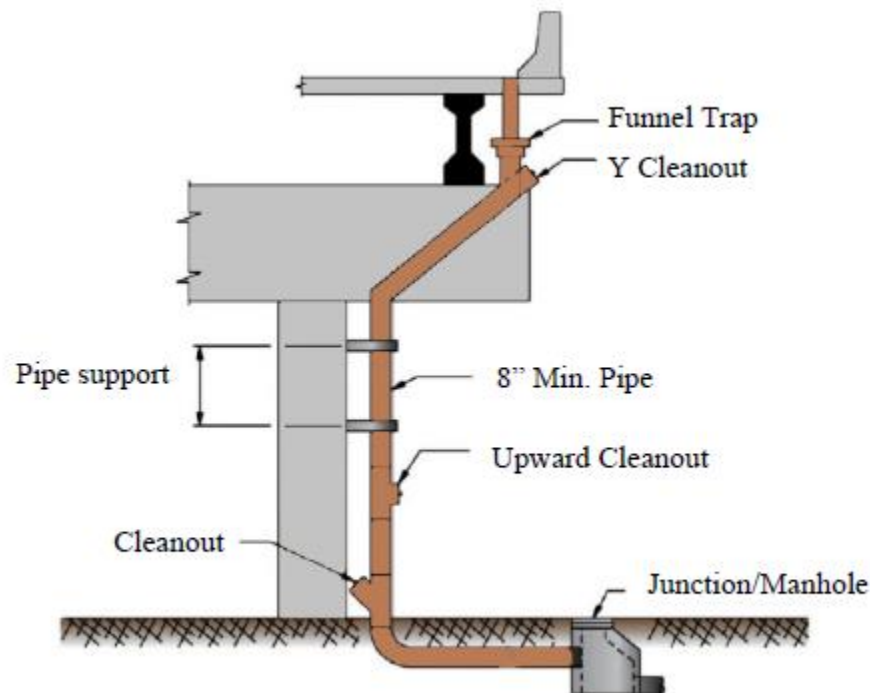


Figure 2.3 Closed Deck Drainage System (modified from FHWA, 2015)

A TxDOT drawing of an elevation view for a closed deck drainage system with its components embedded in the concrete is presented in Figure 2.4. The inlet grate on the bridge deck is cast in place. The pipe is made of polyvinyl chloride (PVC) with a diameter of 6-inches. A splash pan is shown on the ground surface (TxDOT, 2010) to prevent potential surface erosion (Young et al.,

1993). Lastly, bends in this example are fewer than most other available drawings. Minimizing the number of bends helps prevent pipes from clogging (INDOT, 2012).

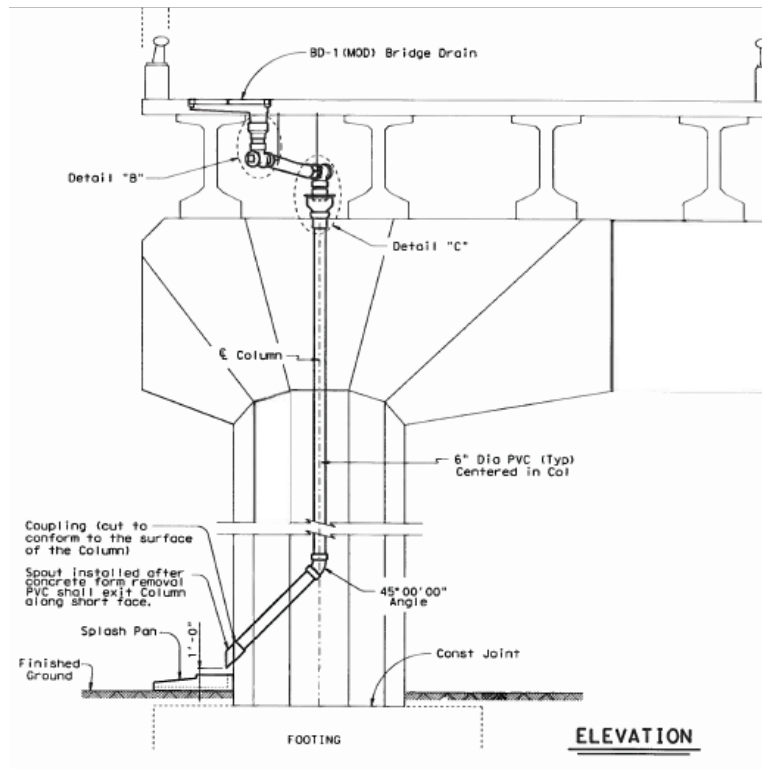


Figure 2.4 Closed deck drainage system components (TxDOT, 2010)

The selection of an open or closed system for bridge deck drainage depends on factors, such as the initial cost and the maintenance frequency. Table 2.1 summarizes the key differences between the two systems that can help engineers select the appropriate drainage system for bridge structures.

Table 2.1 Preliminary evaluation of open and closed systems

Criterion	Open	Closed
Inlet (SCDOT 2006)	Scuppers or grates	Grates
Capturing efficiency (SCDOT 2006)	More efficient	Less efficient
Initial cost (SCDOT 2006)	Lower	Higher
Pipes (FHWA 2012)	Outlet pipe	Downspout pipes
Inlet maintenance (FDOT 2018)	Scuppers clog more (constant maintenance requirement)	Grates clog less (less maintenance requirement)
Chemical contact with superstructures (FDOT 2018)	Yes	No
When to use (FDOT 2018)	No concerns over runoff below the bridge, floods, environmental impacts. No active facilities under the bridge (e.g., railroads, or travel lanes).	Concerns over runoff below the bridge, floods, environmental impacts. Active facilities under the bridge exist.

Open drainage systems allow free-fall. An open system is favorable when there are no concerns about environmental impacts and when no facilities exist underneath the outlet pipe. Open drainage systems reduce maintenance demands because of the minimum use of pipes in conveying the rainfall runoffs to ground drainage systems.

Scupper inlets are only used in open deck drainage systems, and the pipe underneath the scupper inlet is a part of it. The scupper inlet conveys runoff directly onto the ground surface; this makes the design and implementation of an open system with scupper inlets easier compared to closed deck drainage systems. However, opening areas of scupper inlets are typically smaller than those of grate inlets. Hence, scupper inlets are not recommended on bridges where runoffs carry significant amounts of debris.

The bridge deck drainage system comprises bridge decks, gutters, inlets, pipes, and bridge end collectors (INDOT, 2012; Young et al., 1993). These components are further elaborated in the following sections.

2.2 Bridge Deck and Gutters

The bridge deck and gutter surface convey the runoff to a drainage inlet or a bridge end collector. The amount of runoff depends on the size of a bridge deck surface. It is essential to design the superelevation, cross-slopes, and longitudinal profile of the bridge deck to effectively transfer runoff from the bridge deck to the inlet of the deck drainage system (Young et al., 1993). A minimum profile grade of 0.5% and a transverse slope of 2% are desirable for bridge decks (NDOT, 2006; FHWA, 1979). Bridge decks with zero grades and sag vertical curves have poor hydraulic performance and should be avoided (SCDOT, 2006).

2.3 Drainage Appurtenances – Inlets, Pipes, and Downspouts

Bridge drain inlets receive runoff from the decks and gutters, and through pipes and downspouts, the runoff is conveyed to ground drainage structures (Hammonds et al., 1995). The drainage inlets should remove rainfall runoff from the bridge deck before the flow exceeds the gutter capacity (Holley et al., 1992).

Many states in the U.S. use cast iron and fabricated steel to make inlet boxes and scupper inlets; some states specify the dimensions and allow the inlets to be cast in a construction site (Young et al., 1993). The inlet drains in bridges may either be scupper drains, which allow free-fall of the captured runoff, or grated drains with a variety of grate geometries and box sizes beneath the grates (Holley et al., 1992). Figure 2.5 shows examples of a vertical scupper inlet and an offset scupper inlet used for bridge deck drainage systems. The drainage inlets installed in corrosive conditions require heavy galvanization and epoxy coatings (Young et al., 1993).

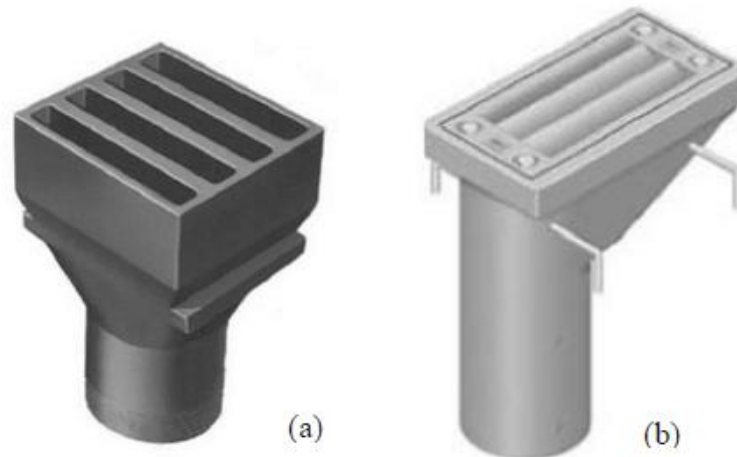


Figure 2.5 (a) Heavy duty vertical scupper inlet (b) Offset scupper inlet with frame and bolted grate (Neenah Foundry Company, 2020)

2.4 Grate Inlets

Typical pavement drainage inlets are not suitable for bridge decks because it is hard to integrate them into the structural dimensions of a bridge deck. Large inlets on bridges cause problems in the design and construction of deck reinforcement; hence, bridge deck drainage inlets are smaller compared to typical pavement drainage inlets. The grates of deck drains are generally made up of cast iron and are typically rectangular or round (FHWA, 2018).

To avoid additional strain on deck drain inlets, the surface runoff outside the bridge structure should be intercepted before entering the bridges. Inlets should be placed at an appropriate spacing to intercept the runoff on bridge decks effectively.

The urban drainage design manual by FHWA introduced eight grate inlets (FHWA, 2013). These eight grate inlets are summarized in Table 2.2. The grate inlets are ranked according to debris handling efficiency, as well as bicycle and pedestrian safety. Rank 1 denotes the best performance in bicycle and pedestrian safety and debris handling efficiency. Rank 7 in the bicycle and pedestrian safety column is the least safe but is considered safe, nonetheless. Rank 8 in the debris handling efficiency column is the least efficient compared to the other grate inlets reviewed.

Table 2.2 FHWA grate inlets safety ranking (FHWA, 2013)

Grate	Rank of debris handling efficiency	Rank of bicycle and pedestrian safety	General notes
P-50 parallel bar grate	4	Not safe	- Hydraulically superior to all other grate types in this table - Not bicycle safe - Bar spacing 1 - 7/8 inches on center
P-50 X 100 parallel bar grate	5	1	- hydraulically effective at low velocities - Bicycle safe - Bar spacing 1 – 7/8 inch on center, and 3/8-inch diameter lateral rods spaced at 4 inches on center
P-30 parallel bar grate	8	3	- Good hydraulic features with high velocity flows - Bicycle safe, but caution is advised with narrow racing bicycle tires - 1 – 1/8 inch on center bar spacing
Curved vane	1	6	- Good hydraulic features with high velocity flows. According to PennDOT, it has the best capturing efficiency (PennDOT, 2010) - Bicycle safe - 3 – 1/4 inches longitudinal bar and 4 – 1/4 inch transverse bar spacing on center - Care must be taken during installation to avoid mistakenly placing it 180 ° out of proper alignment. Improper alignment will reduce the inlet’s interception capacity and may become more prone to clogging (Young et al., 1993) - Tilted vanes are better than non-tilted, and curved vanes are better than tilted vanes (Young et al., 1993)

Table 2.2 FHWA grate inlets safety ranking (FHWA, 2013) (cont'd)

Grate	Rank of debris handling efficiency	Rank of bicycle and pedestrian safety	General notes
45°-60° tilt bar	6	5	- Hydraulically effective at low velocities - Bicycle safe - 2 – ¼ inch longitudinal bar and 4-inch transverse bar spacing on center
45°-85° tilt bar	3	4	- Hydraulically effective at low velocities - Bicycle safe - 3 – ¼ inch longitudinal bar and 4-inch transverse bar spacing on center
30°-85°	2	7	- Hydraulically effective at low velocities - Bicycle safe - 3 – ¼ inch longitudinal bar and 4-inch transverse bar spacing on center
Reticuline “Honeycomb”	7	2	- Hydraulically effective at low velocities - Bicycle safe - Honeycomb pattern of lateral bars and longitudinal bars

Figure 2.6 shows the reticuline grate inlet, which has a honeycomb pattern and is considered bicycle safe (FHWA, 2013).

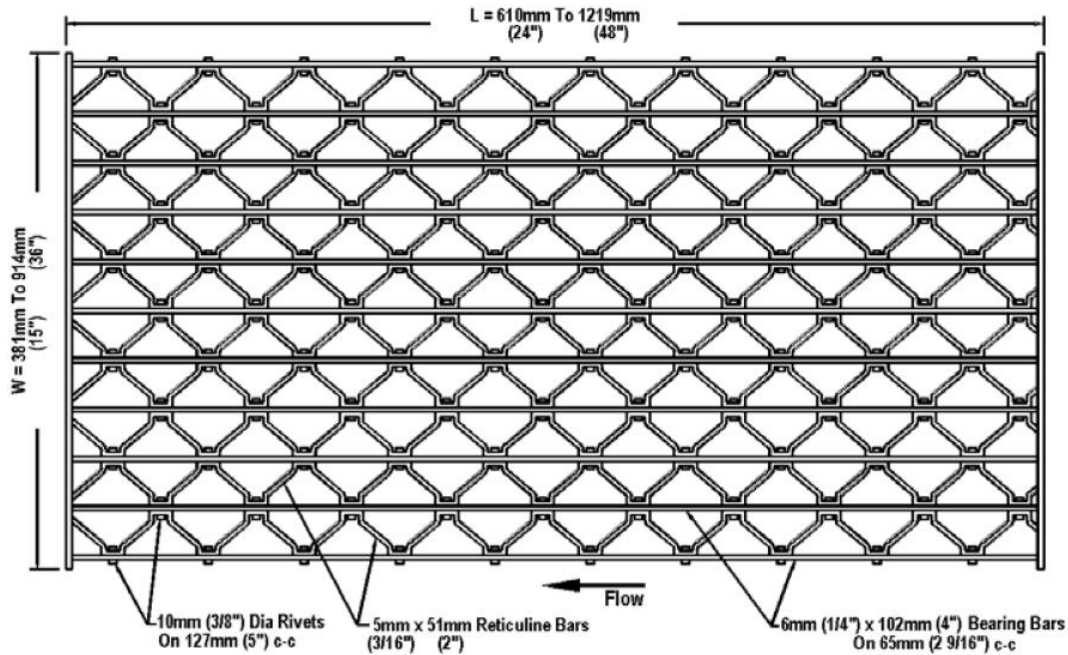


Figure 2.6 Reticuline “Honeycomb” grate inlet (FHWA, 2013).

Hydraulic efficiency is defined as the ratio of interception capacity of the inlet to the total flow (CDOT, 2012). The hydraulic efficiencies for the eight previously mentioned grates were obtained from lab tests and should not be used for field performance (FHWA, 2013). The interception capacity, grate type selection, inlet efficiency (Young et al., 1993), and interception along the side of the grate (FHWA, 2013) depend on different factors summarized in Figure 2.7.

Interception Capacity	Grate Type Selection	Inlet Efficiency	Interception Along the Side of the Grate
<ul style="list-style-type: none"> • Depends on: <ol style="list-style-type: none"> 1. Amount of water flowing over the grate. 2. Size and configuration of the grate. 3. Velocity of flow in the gutter. 	<ul style="list-style-type: none"> • Depends on: <ol style="list-style-type: none"> 1. Hydraulic efficiency. 2. Debris handling. 3. Pedestrian and bicycle safety. 4. Loading conditions (must withstand traffic loads). 5. Relative costs. 	<ul style="list-style-type: none"> • Depends on: <ol style="list-style-type: none"> 1. Cross slope. 2. Longitudinal slope. 3. Total gutter flow. 4. Pavement roughness (to a lesser extent). 5. Size and configuration of the grate. 6. Amount of water flowing over the grate. 	<ul style="list-style-type: none"> • Depends on: <ol style="list-style-type: none"> 1. Cross slope. 2. Length of grate. 3. Flow velocity.

Figure 2.7 Factors revolving around grate inlets

Information about the capturing efficiency for grate inlets can be obtained from their manufacturers (Young et al., 1993). Grates with bars parallel to traffic are the most hydraulically efficient, but bars should be perpendicular to traffic if bicycle safety is a concern. Perpendicular bar grates can be made more efficient with vane grates (making the bars vaned). Vanes are tilted with the top edge inclined in the upstream direction (FHWA, 2018). Figure 2.8 shows the grate vane details (TxDOT, 2020).

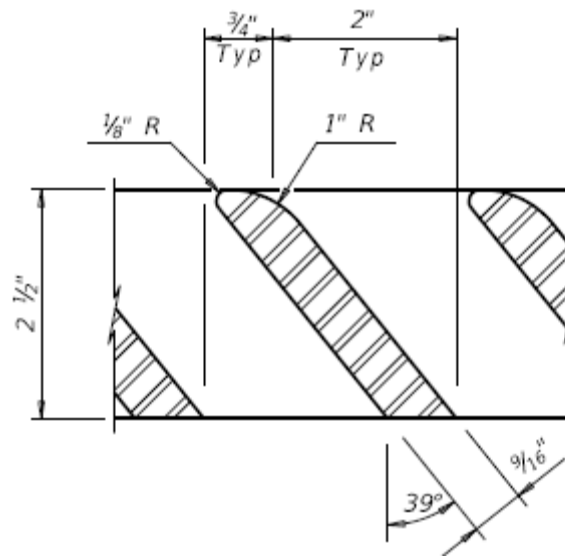


Figure 2.8 Grate vane details (TxDOT, 2020)

When the flow velocity is higher than the splash-over velocity (minimum velocity causing some water to shoot over the grate (FCGOV, 2002)), only part of the flow will be intercepted. If the flow velocity is high, inlets with longer lengths must be provided to allow all the water to drop in the box. Otherwise, splash-over will occur. Generally, longer inlets should be provided for bridge decks with steep slope gutters (FHWA, 2018). For slopes over 2%, reticuline grates' interception capacity will decrease, and splash-over will occur. On slopes over 6%, splash-over will occur on all grates, except parallel bar and curved vane grates. On moderate slopes, all the grates perform equally (Young et al., 1993).

2.4.1 Sag Locations

From a hydraulic point of view, sags on bridge decks are undesirable (Young et al., 1993). However, there are some recommendations to alleviate the problems at sag locations. At sag vertical curves, grates act as weirs for shallow ponding depths and as orifices at greater depths (FHWA, 2018). They work as weirs up to a depth of 0.4 feet and as orifices when depth exceeds 1.4 feet. Between the depths of 0.4 and 1.4 feet, the transition occurs (Young et al., 1993). This transition decreases the interception capacity (MnDOT, 2000).

Ponding can occur at sag locations. Placing flanking inlets on each side of the sag inlet is recommended. Flanking inlets limit the spread on low gradient approaches to the level point (Young et al., 1993). The spread is defined as a measure of the transverse lateral distance from the curb face to the limit of the water flowing on the roadway (FHWA, 2013). Flanking inlets also act as a relief for the inlet at the low point of the sag location should the design storm be exceeded or clogging occur (Young et al., 1993).

2.4.2 TxDOT Bridge Deck Drainage Inlets

Texas Department of Transportation's Bridge Standards (TxDOT, 2020) show the standard drawings for the typical grate inlets used in the state. Table 2.3 summarizes important properties observed from the TxDOT grate inlet standard drawings (TxDOT, 2020):

Table 2.3 Properties of TxDOT grate inlet standard drawings (TxDOT, 2020)

Grate Property	Cast Inlet	Welded Inlet	Welded with Cast Options
Number of grate openings	8	10	27
Grate rotation	180°	180°	180°
Drain opening area	300 sq in	350 sq in	173 sq in
Galvanized	✓	✓	✓

Manufacturers have their own designs of grate inlets. Their designs vary; each design has its own set of specifications (TxDOT, 2019). The grate inlet rotation of 180° makes maintenance access to the drainage system a lot easier and accommodates assembly in the field (TxDOT, 2020).

2.4.3 SCDOT Bridge Deck Drainage Inlets

South Carolina Department of Transportation classifies the design to open and closed systems (SCDOT, 2006):

- For open systems, it is typical to use 6-in diameter scupper inlets for bridge inlets. Scupper inlets may be made of fiberglass or PVC. If sidewalks exist on a bridge, grate inlets should be used instead of scupper inlets. At sag locations or superelevation transitions, scupper inlets are not permitted.
- For closed systems, grate inlets are used.

2.4.4 INDOT Bridge Deck Drainage Inlets

Indiana uses different inlet designs for various applications (e.g., bicycle safety, hydraulic efficiency.) Table 2.4 shows inlets used by INDOT on bridge decks:

Table 2.4 INDOT bridge deck drain inlets (INDOT, 2012)

Grate A	<ul style="list-style-type: none"> - Design has parallel bar grates - Most hydraulically efficient - Not bicycle safe - If bars are perpendicular to the traffic, it becomes bicycle safe. However, the hydraulic capacity will be substantially reduced - Dimensions: 19 x 19 in - Outlet fitting is a 6 in. diameter circular pipe
Grate D	<ul style="list-style-type: none"> - Design has parallel bars with two transverse bars - Bicycle safe - Dimensions: 19 in. wide by 20 in. long - Outlet fitting is a 6 in. diameter circular pipe
Slab-Bridge Floor Drain	<ul style="list-style-type: none"> - Used on reinforced-concrete slab bridges - Drain: 6 in. PVC pipe in the bridge deck - Spacing closer than other types due to limited hydraulic capacity of drain - Standard spacing: 72 in. - A ½ in. depressions that extends 1 ft transversely from the face of the curb increases the capacity
Concrete-Barrier-Railing Scupper	<ul style="list-style-type: none"> - Only used on a local public agency bridge with concrete-barrier railings

2.4.5 Maintenance of Bridge Deck Inlets

Grate inlets are easy to remove, which provides easy access to the drainage system. Grate inlets and scupper inlets require constant regular maintenance to remove debris (TxDOT, 2019). Debris carried by the runoff clogs the inlet of the drainage system. Standing ponds can occur if enough debris is collected on the grate, reducing the clear grate opening area. From a hydraulic point of view, it would be better for inlets to be large and widely separated. From a structural point of view, smaller inlets are desirable to maintain the structural integrity of bridges. The spread of 8 to 12 feet of water in gutters is not effectively reduced with small inlets. Multiple closely spaced inlets are needed when expecting a spread this high. Heavy galvanizing or epoxy coating are recommended to avoid corrosion (Young et al., 1993).

2.5 Pipe and Downspouts

The water entering bridge drain inlets is conveyed to the ground drainage systems through pipes and downspouts. The collector pipe and downspouts should be designed to prevent clogging and minimize the corrosion on the pipe materials (INDOT, 2012). The drainage pipes buried in concrete or concealed within the structure presents maintenance problems. A designer should be cautioned against placing the drainage system embedded within the superstructure (Iowa DOT, 2014). The collector pipe slope must be designed to obtain the self-cleansing velocity (SCDOT, 2006). T-Connection and bends should be minimized to prevent clogging in pipes (INDOT, 2012). Cleanouts (Figure 2.3) should be provided at a suitable interval in the closed deck drainage system.

According to the hydraulic design of safe bridges by FHWA, underdeck drainage pipes are usually ductile iron, polyvinyl chloride (PVC), or fiberglass (FHWA, 2018). Still, steel pipes are also common in some states (e.g., Florida and Virginia).

In an open deck drainage system, downspouts should extend below the superstructure and be placed away from piers to avoid wind-driven sprays on bridge members (Young et al., 1993). The pipes in an open drainage system allow the water to fall freely to the ground surface. Free-falls over 25 feet will disperse the water enough so that no erosion will occur. When free falls are less

than 25 feet, splash blocks may be needed to prevent potential surface erosion (Young et al., 1993). Table 2.5 provides examples of pipe materials commonly used in different states. The polyvinylchloride (PVC) pipe is the most common pipe material selected for the bridge deck drainage system.

Table 2.5 Examples of pipe materials commonly used across the states in bridge deck drains

State DOT	PVC	Fiberglass	Ductile Iron	Steel
TxDOT (2014)	✓			
FDOT (2017)	✓	✓	✓	✓
VDOT (2020)				✓
SCDOT (2006)		✓		
MnDOT (2020)	✓			
INDOT (2012)	✓			
NCDOT (2018)	✓			✓

Figure 2.9 displays drainpipes in a closed bridge deck drainage system.



Figure 2.9 Bridge Deck Drainage Pipes (Hennegan & Associates, 2020)

Many factors are critical for selecting pipe material. These factors include cost, durability, strength, service life, and corrosion resistance. Table 2.6 summarizes the advantages and disadvantages of the different pipe materials.

Table 2.6 Advantages and disadvantages of pipe materials

Pipe	Advantages	Disadvantages
PVC	<ul style="list-style-type: none"> - Low cost with high availability - Lightweight - Resists corrosion - Fittings not limited to standard angles - Ease of installation - Economical - Flexible 	<ul style="list-style-type: none"> - Costly repairs - Sensitive to temperature changes and construction temperatures - Impact damage in cold weather results in rapid crack propagation - Vulnerable against chemical attacks - Unless ultra-violet light (UV) protected, strength will decrease over time
Ductile Iron	<ul style="list-style-type: none"> - Ease of installation - Great long-term performance (over 100-year service life) - High strength - 100% recyclable 	<ul style="list-style-type: none"> - Pipe leakage - SBR (red rubber) gaskets are subject to chemical attacks - Connections will leak if not fused correctly - Heavy

Table 2.6 Advantages and disadvantages of pipe materials (cont'd)

Pipe	Advantages	Disadvantages
Steel	<ul style="list-style-type: none"> - Low cost and high availability - Recyclable and environmentally friendly - Durable 	<ul style="list-style-type: none"> - Corrosion - Labor demanding - Repairs are costly - May leak
Fiberglass	<ul style="list-style-type: none"> - Strong resistance to corrosion - Smooth surface for better flow velocity - Ease of installation - Low maintenance cost - Service life of over 50 years - Heat resistant - UV absorbent added on the surface - Effective anti-freezing - Lightweight (ease of transportation) 	<ul style="list-style-type: none"> - Low elastic modulus - Poor long-term temperature resistance (decrease in strength) - In time, chemicals, UV light, wind, and rain will decrease the pipe's performance
References	Lake County, IL (2014), EPA (2000), Airpro (2017), World Iron Steel (2020), Ductile Iron Pipe Research Association (2020), Mid City Steel (2013), James Dunkerley Steels (2018)	

2.5.1 Aesthetics

The pipe system affixed to the exterior of the bridge surface can debase the bridge aesthetics (Young et al., 1993). On the other hand, it is not desirable to enclose the pipes in the structural members because of potential freezing damage and difficulty in maintenance (thorough cleaning and flushing) (Iowa DOT, 2006). It is essential to have a drainage system that preserves bridge aesthetics while conveying the rainfall runoff from the bridge to the ground drainage inlet. To preserve the bridge aesthetics, the pipes are usually hidden in the decorative plasters or run-in slots up the back of the columns (INDOT, 2012). Figure 2.10 shows how pipes can be painted the same

color as the bridge deck to make them aesthetically pleasing. Pipes painted the same color as the bridge deck increase safety by minimizing drivers' distractions.

Specific guidelines were established by the Minnesota Department of Transportation for pipes to be aesthetically pleasing (MnDOT, 1995). The guidelines are:

- Minimizing the number of fittings.
- Concealing the pipes between beams.
- Placing drains on the least visible side of piers.
- Painting pipes the same color as the structure they are mounted on.
- Running the pipes along or at right angles to the main line of the structure.



Figure 2.10 Pipes along the bridge deck with the same color as the steel beams (Vlčeka, 2012)

2.5.2 Maintenance and Repairs

One of the major concerns in pipes is clogging due to debris collections. Bends and T-connections should be minimized to prevent the accumulation of debris in pipes. The minimum permitted slope for bridge deck drainage pipes is 2%. To achieve self-cleansing velocities for 6-in and 8-in diameter pipes, an 8% slope is recommended. Self-cleansing velocities assist in removing sand,

silt, and other collected materials (Young et al., 1993). 8-in pipes are preferred to 6-in pipes to prevent clogging in the pipes (Iowa DOT, 2020). Table 2.7 shows maintenance and repair procedures in Florida and Iowa, as well as FHWA guidelines for bridge deck drainage pipes (FDOT, 2018; Iowa DOT, 2014; FHWA, 2012).

Table 2.7 Maintenance and repair practices on bridge deck drainage pipes

Measure	FDOT Practice	Iowa DOT Practice	FHWA Guidelines
Regular maintenance	<ul style="list-style-type: none"> - Remove debris from the inlet location using a snake - Using high-pressure jets to flush (Figure 9), with flushing optionally accompanied, at the cleanouts to remove debris and clogging 	<ul style="list-style-type: none"> - Remove debris with hand or hand tools - Clear obstructions using high-pressure water, or compressed air, or drain snake - Flush drains - Replace cleanout plugs 	<ul style="list-style-type: none"> - To remove debris from pipes, use plumber snakes. Flushing with compressed air is done after using the plumber snake - The compressed air must be controlled to avoid any damage to the pipes - Remove cleanout plugs, and dislodge with water, snakes, or “roto-rooter” to remove debris
Repairs	<p>Clogged Pipe replacement:</p> <ul style="list-style-type: none"> - Due to severe clogging, orthogonal pipes may be replaced. Small radius bends can also be replaced with bigger ones for transition and easy cleanouts access - Replacing pipes with bigger diameter ones to decrease frequent clogging 	<p>Damaged Pipe replacement:</p> <ul style="list-style-type: none"> - Remove the damaged part with a torch - Grind the free ends to remove burs - Either couple in a new section of steel drainpipe or connect double-walled corrugated PVC pipe using pipe clamp bands 	<p>FHWA Refers to MnDOT practice for Drain Extension (MnDOT):</p> <ul style="list-style-type: none"> - Cut box beam and weld in place - Hold extensions in place using brackets bolted to the bottom of the deck and other brackets bolted to the web of the beam

Cleanouts should be installed at locations that help remove obstructions. Downspouts should be installed at locations accessible for maintenance operations. It is preferred that the downspouts be located so that maintenance can be done from the ground (INDOT, 2012). Flushing is typically done by high-pressure jets (Figure 2.11). The two main jet nozzle types are forward and rear jets; forward jets are used to penetrate blockages in the pipes, and rear jets provide nozzle propulsion while cleaning the drainpipe wall surface (FDOT, 2018).

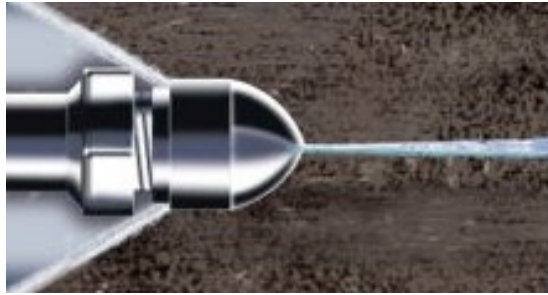


Figure 2.11 Forward Jet Nozzle for Flushing (Drain brain company, 2020)

The forward jet nozzle is used for clogged pipes, while the rear nozzles are used for non-clogged pipes (FDOT, 2018). Compressed air may also be used for flushing. Before using compressed air, a plug is typically installed at the lower end of the drainpipe to make it airtight (FDOT, 2018).

TxDOT uses Vactor (vacuum) trucks (Figure 2.12), as well as debris storage bins for cleaning bridge deck drains and storing debris away.



Figure 2.12 Vactor trucks (Vactor, 2021)

Vactor trucks are equipped with high-pressure water pumps to perform hydraulic cleaning on bridge deck drains. Hydraulic cleaning is done on drain inlets, downspouts, sump boxes, and storm sewers.

According to Iowa DOT, pipe extensions can also be provided for steel pipes by removing the existing steel drainpipe and following one of these two recommendations:

- Fit an oversized PVC pipe over the steel pipe extension and attach it to the bottom of the bridge deck using L-brackets and stud anchors.
- Attach a double-walled corrugated PVC pipe using pipe clamp bands.

2.6 Previous TxDOT Research

Research and lab tests were done on different inlets and drains to determine their hydraulic characteristics, create predictive equations for inlet performance, and improve bridge deck

drainage. The following subsections summarize the results of three TxDOT research projects focused on bridge deck drains:

2.6.1 Hydraulic Characteristics of Recessed Curb Inlets and Bridge Drains (Holley et al., 1992)

Holley et al. (1992) evaluated a rectangular scupper inlet for open systems and two grate inlets for closed systems. Their objective was to create predictive equations for the performance and the capacities of the drains. Using lab experiments and regression analysis, the flow into the inlet was determined as a function of the upstream uniform flow depth, the longitudinal roadway slope, and the cross slope (Holley et al., 1992).

2.6.2 Hydraulic Performance of Small-Scale Bridge Deck Drains (Qian et al., 2013)

Qian et al. (2013) evaluated the performance of a rectangular scupper inlet developed by TxDOT. The scupper was made up of a drain pan and a drain grate. The grate was placed over the drain pan to prevent clogging and provide safety for cyclists and pedestrians. Figure 2.13 shows TxDOT's scupper inlet, which can be used for both open and closed bridge deck drains. The scupper inlet can be used on long bridges, bridges in urban areas with traffic or pedestrian features, and bridges above environmentally sensitive areas (Qian et al., 2013).



Figure 2.13 TxDOT rectangular deck drain (scupper) (Qian et al., 2013)

The hydraulic performance for the rectangular scupper was studied using lab tests; an accurate equation was created to guide the design of rectangular scuppers (Qian et al., 2013). The data measured from the lab tests indicated that a weir type equation should be used to predict the capturing discharge. Hydraulic performance was seen to increase with drain size and number of drains. If the drain size and number of drains are fixed, the capture discharge increases with the increase of the cross slope. However, the capture discharge decreases with the increase of the longitudinal slope (Qian et al., 2013).

2.6.3 Hydraulic Characteristics of Flush Depressed Curb Inlets and Bridge Deck Drains (Hammonds et al., 1995)

Hammonds et al. (1995) followed up on the research conducted by Holley et al. (1995). Extensive tests were conducted on two bridge deck drains (drain 2B and drain 4) for different flow rates, cross slopes, and longitudinal slopes (Hammonds et al., 1995). Figure 2.14 shows the plan and cross-section of drain 2B. Drain 2 from Holly's study in 1992 (Holley et al. 1992) and drain 2B are the same, except for their opposite orientations shown in Figure 2.15 (Hammonds et al., 1995).

The results showed that drain 2 and drain 2B both exhibit a transition from the weir to orifice flow. The transition in drain 2B was gradual, unlike drain 2. However, drain 2B showed less capacity than drain 2 because the shallow part of drain 2B was located next to the curb. Nevertheless, both drains showed equal capacities for low approach flow rates when both drains were in the weir control regime (Hammonds et al., 1995).

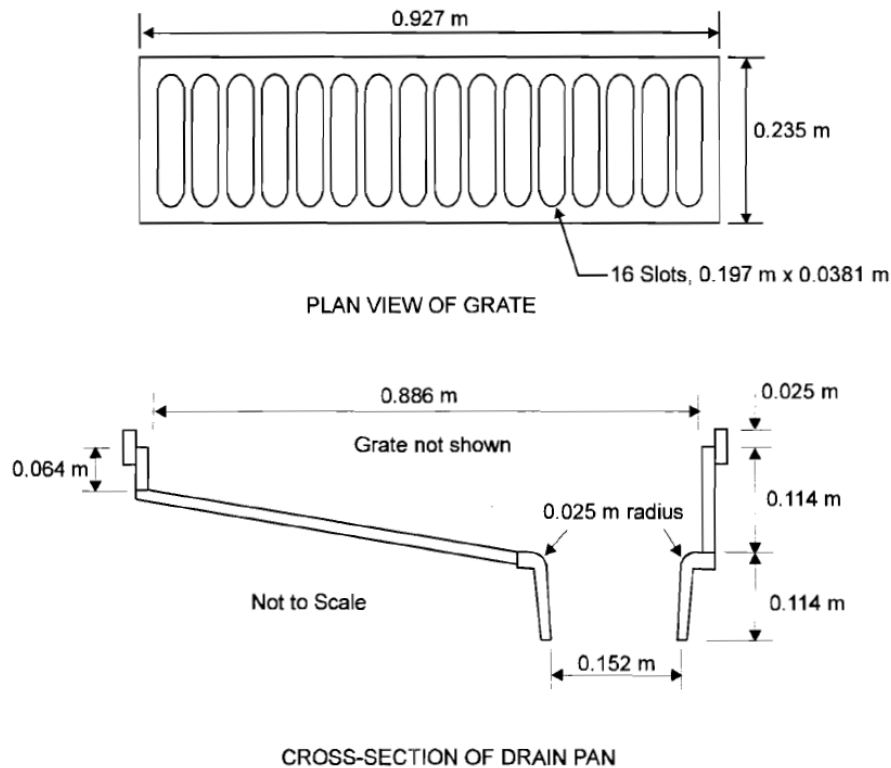


Figure 2.14 Plan and cross-section of drain 2B (Hammonds et al., 1995).

An equation to predict the capacity was created for drain 2B that works for both weir and orifice flow since the transition between them was gradual (Hammonds et al., 1995). The experiment results showed that the capacity of drain 2B was significantly less than that of drain 2 because of the different orientations, as shown in Figure 2.15. But the capacity of drain 2B can be improved by using a deeper, larger drain pan (Hammonds et al., 1995).

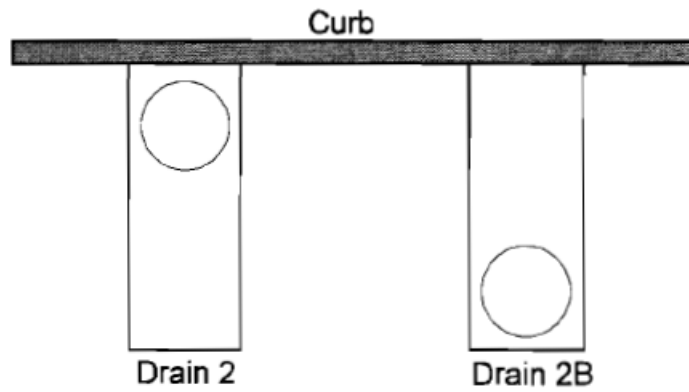


Figure 2.15 Orientation of drain 2 and drain 2B (Hammonds et al., 1995)

Drain 4, developed by TxDOT, has a larger drain pan (Figure 2.16) than drain 2B and has a grate (Figure 2.17) with transverse bars inclined in the direction of the approach flow (Hammonds et al., 1995).

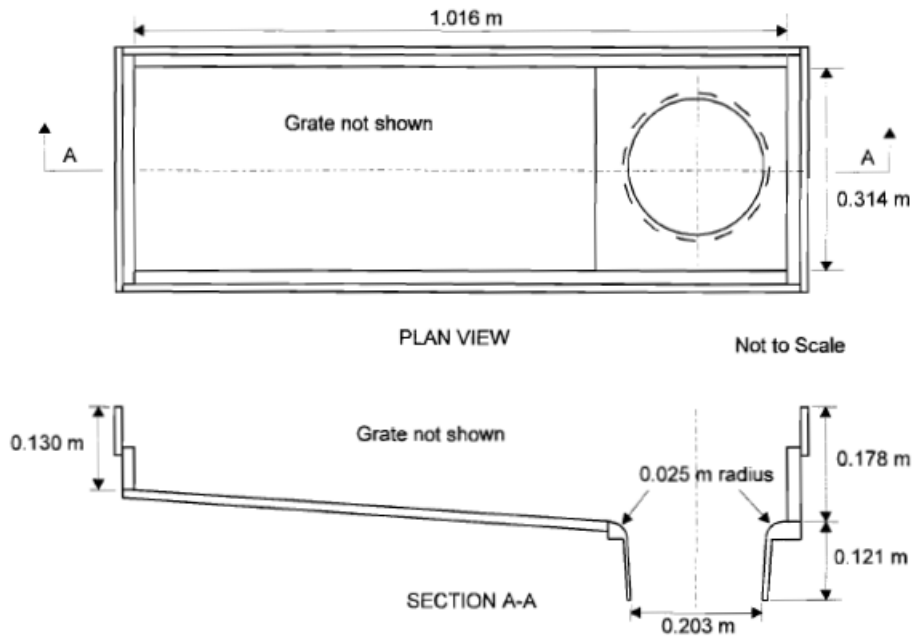


Figure 2.16 Drain 4 pan

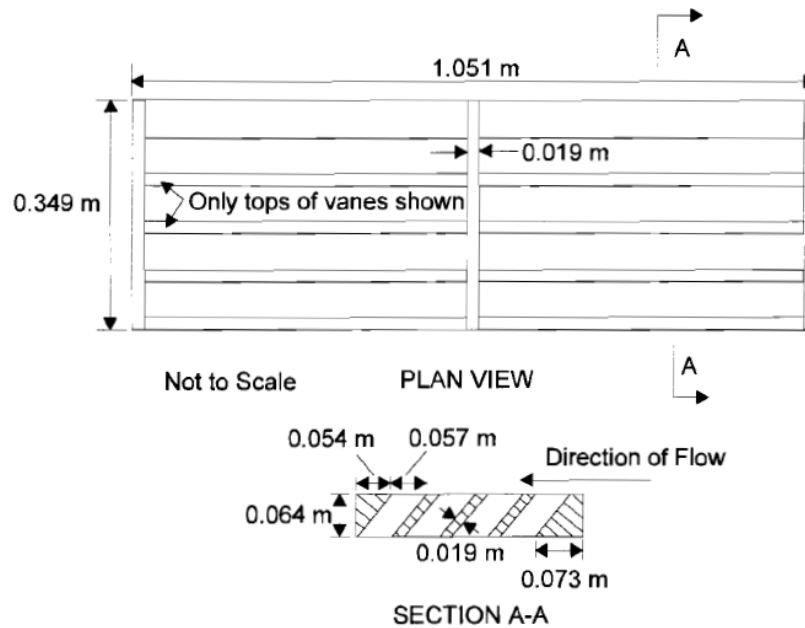


Figure 2.17 Drain 4 grates

Drain 4 gave a much higher capacity than drain 2B. The main design reasons for drain 4 having a higher capacity were the deeper drain pan and the larger outlet pipe. Equations were developed for drain 4 to predict the performance and the capacity (Hammonds et al., 1995).

2.7 Hydroplaning

Wet bridge deck surfaces can cause skidding or sliding of the car tires. A rainfall runoff causes sheet flow or spread of water in the bridge deck. If enough water depth is accumulated to separate tires from the bridge deck, tires lose traction, increasing the chance of hydroplaning (Young et al., 1993). The runoff from the bridge deck should be drained to reduce the risk of hydroplaning of vehicles.

Hydroplaning depends on water depths (depending on the drainage design and condition), roadway geometrics, vehicle speeds, tread depths, tire inflation pressure, and the conditions of the pavement

surface (Young et al., 1993). According to AASHTO policies of highway design, the following considerations can help minimize hydroplaning of vehicular traffic (VDOT, 2019):

1. Maximize cross-slope
2. Limit spread by decreasing inlet spacing
3. Maximize interception of gutter flow above superelevation transitions
4. Limit duration and depth of ponded water in sag locations
5. Limit depth and duration of overtopping flow

TxDOT recommendations for minimizing hydroplaning (TxDOT, 2019) are:

1. Proper cross-slopes
2. Conscientious placement of inlets
3. Permeable surface courses and high macrotexture surface courses
4. Transverse grooving

Table 2.8 summarizes the variables influencing hydroplaning (FHWA, 1979).

Table 2.8 Variables influencing hydroplaning (FHWA, 1979)

Factors Within the Engineer's Control	Factors Outside the Engineer's Control
Surface Texture	Rainfall
Cross-Slope	Tire Tread and Depths Pressures
Drainage Path Length	Vehicle Speeds (can be influenced, but not fully controlled)

Water depths should be minimized through proper drainage, and cross-slopes should be maximized for reducing hydroplaning. Table 2.9 discusses the previously mentioned criteria (water depths and cross-slopes).

Table 2.9 Criteria related to bridge deck drainage affecting hydroplaning (FHWA, 1979)

Criterion	General Notes
Water Depth	<ul style="list-style-type: none"> - Traction decreases smoothly with the increase of water depth until full loss of contact occurs; at that vehicle speed, traction becomes equal to the freewheeling hydrodynamic drag - In puddles of 1-inch depth and 30-foot long, loss of contact may occur at speeds between 40 and 45 mph
Cross-Slope	<ul style="list-style-type: none"> - Increase in cross-slope barely increases frictional demands of the vehicle along a tangent path - Adequate cross-slope is essential when dealing with surface runoff - Minimum cross-slope value is 2%

The established conclusion from this section is that a well-designed drainage system is essential to avoid hydroplaning, especially at sag locations. It is also crucial to provide adequate cross-slopes to drain runoff from the deck surface, with a minimum cross-slope value of 2%.

CHAPTER 3 - SURVEY ANALYSIS ON BRIDGE DECK DRAINS

3.1 Introduction

Two surveys were created to collect the drainage practice data of bridge decks in both Texas and nationwide. The survey questionnaires comprise six sections: participants' contact information, bridge deck drain failures, bridge deck drain design, bridge deck drain construction, bridge deck drain maintenance and inspection, and follow-up interviews. The principal investigator (PI) acquired the Institutional Review Board (IRB) approval before distributing the surveys. The in-state survey was distributed among TxDOT personnel. Forty-five responses have been collected from 17 TxDOT districts. The out-of-state survey was distributed among relevant Transportation Research Board (TRB) committees. Thirty-four responses from 21 different states, the District of Columbia (DC), and Quebec, Canada, have been collected. The research team used the online surveying platform QuestionPro. The in-state and out-of-state survey questionnaires can be found in Appendix A and Appendix B, respectively.

3.2 Survey Questionnaire

The surveys start with a brief description of the project "Synthesis: Bridge Deck Drains" followed by six individual sections. Section 1 (contact information) of surveys asks about the participants' contact information. Section 2 (failure) starts with a brief description of closed bridge deck drainage systems. The description explains two types of closed systems: hung on the exterior of the bridge and embedded in concrete columns. Section 2 asks about the frequency and duration of floods, as well as the recurring bridge deck drain problems. Section 3 (design) asks about the reasons for selecting closed systems, then becomes more specific, and asks about the reasons for using hung and embedded closed systems. This section in the out-of-state survey also includes questions about pipe materials, their advantages, and their common problems. This section ends by asking about respondents' priorities for design improvements. Section 4 (construction) includes open-ended questions about positive and negative construction practices that affect the performance and the service life of bridge deck drains. Section 5 (maintenance and inspection) asks about bridge deck drain maintenance and inspections. This section includes questions about

maintenance methods, inspection schedules, inspection types, available inventory data, runoff end locations, and equipment for cleaning bridge deck drains. Finally, section 6 asks participants if they are interested in participating in a follow-up interview.

3.3 Survey Responses

The responses in this section are presented in the same order as the survey questionnaires. The responses start with the location and position of each participant, then moves on to failure, design, construction, and maintenance of bridge deck drains. Information about participants who were willing to have follow-up interviews is presented in the final subsection of the results. The graphs in blue and green show the results collected from Texas and outside of Texas surveys, respectively.

3.3.1 Respondents' Locations and Positions

TxDOT Participants

The survey collected information about the locations and positions of respondents. Forty-five responses from 17 different TxDOT districts have been collected. Figure 3.1 shows the locations and positions of the survey respondents in Texas.

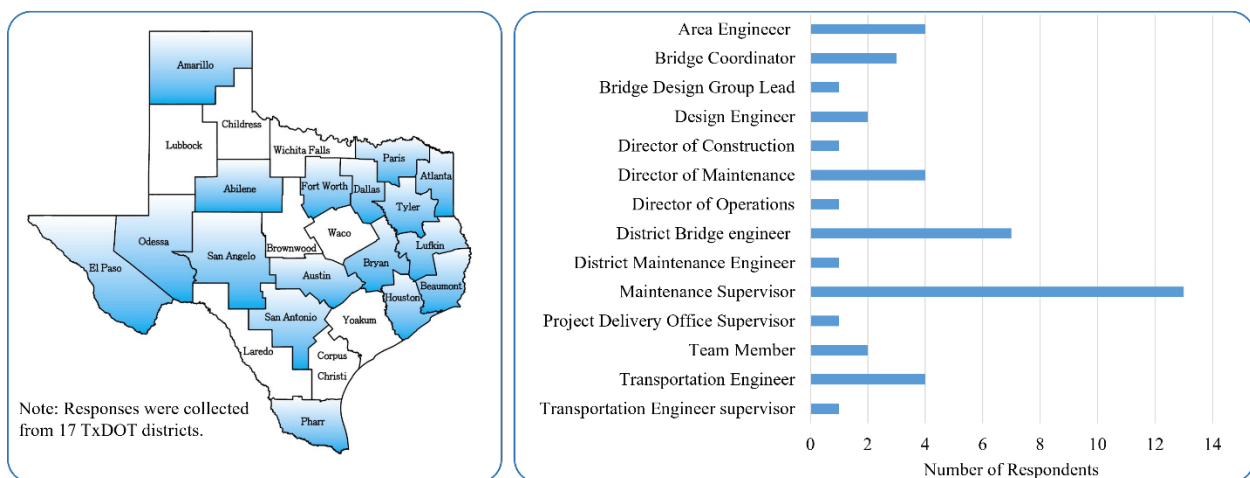


Figure 3.1 Districts (Left) and positions (Right) of survey participants (Texas)

Out-of-State Participants

Figure 3.2 shows the states and positions of the respondents in the United States (excluding Texas). Thirty-four responses from 21 different states (other than Texas), the District of Columbia (DC), and Quebec, Canada have been collected.

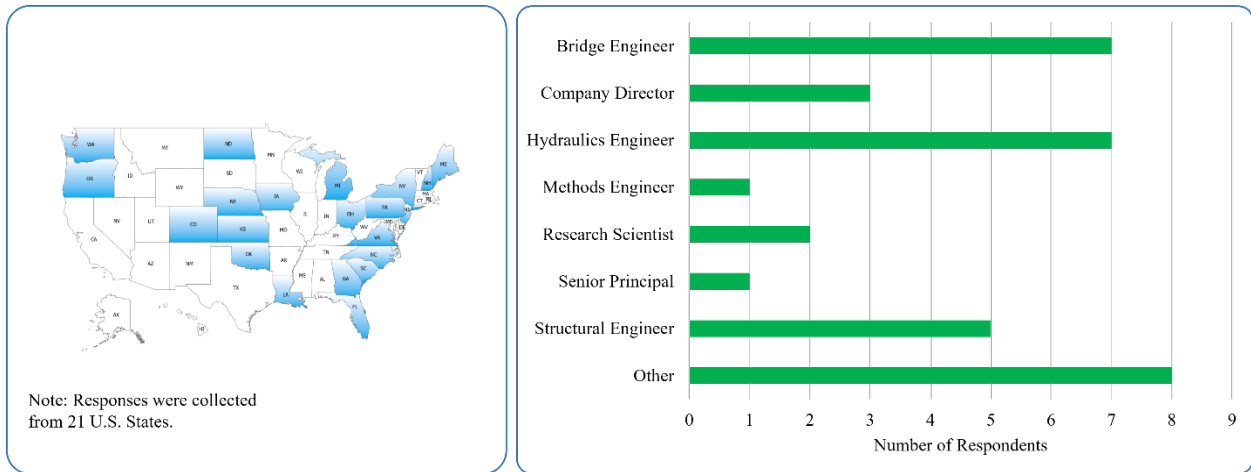


Figure 3.2 U.S. States (Left) and positions (Right) of survey participants (excluding Texas)

3.3.2 Bridge Deck Drain Failure

In-State Results

The TxDOT survey responses for the evaluation of bridge deck drain failures are summarized in Figure 3.3. Figure 3.3 shows that bridge flooding usually occurs during rare and severe rainfalls. The flooding often lasts for less than 30 minutes. 76% of total respondents identified clogging of inlets as the most significant problem associated with the bridge deck drains.

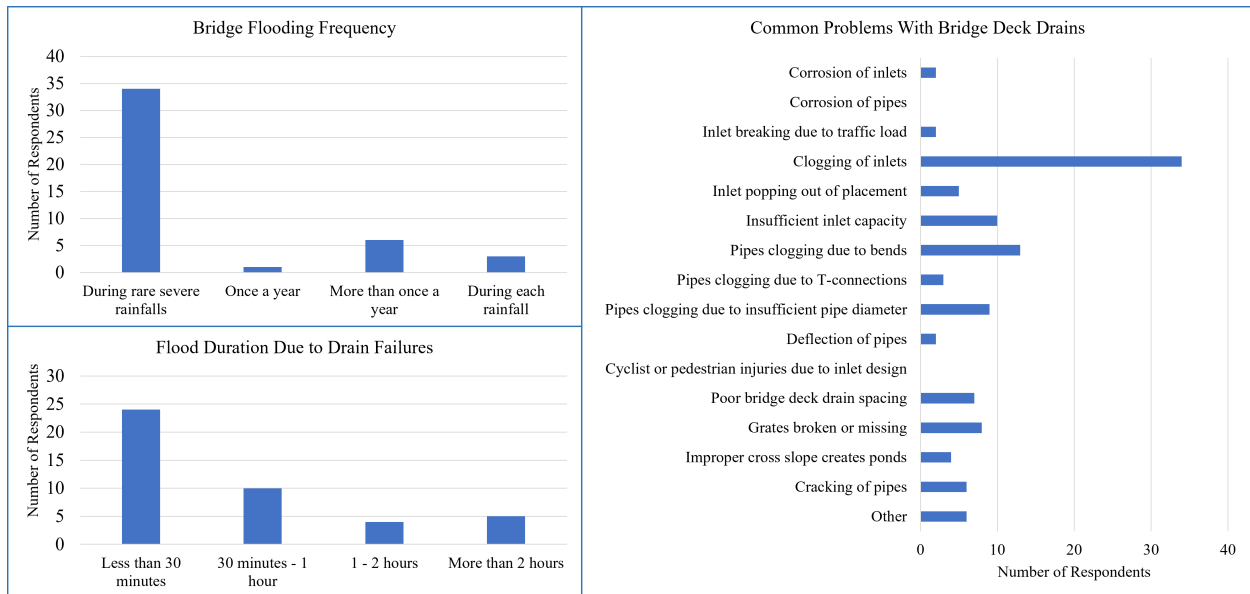


Figure 3.3 Summary of survey responses on bridge deck drain failure (Texas)

Survey respondents also identified other problems in bridge deck drains in addition to the problems included in the survey questionnaire. Other problems identified by survey respondents include corrosion of pipe hanger connections, inlets overlaid by asphalt, and insufficient outlet capacity.

Out-of-State Results

The out-of-state survey responses for the failure section are summarized in Figure 3.4. Figure 3.4 indicates that flooding on bridges usually occurs only during rare severe rainfalls. The flooding mostly lasts less than 30 minutes but can reach up to 2 hours in some states. The most common problems are clogging of inlets (94%), clogging of pipes due to bends (64%), clogging of pipes due to insufficient pipe diameter (50%), corrosion of pipes (41%), and corrosion of inlets (38%). Clogging of inlets was the most common problem with bridge deck drains found in both surveys.



Figure 3.4 Summary of survey responses on bridge deck drain failure (outside Texas)

3.3.3 Bridge Deck Drain Design

In-State Results

Survey responses of participants from 17 TxDOT districts on evaluation of bridge deck drain design are summarized in Figure 3.5. Twenty-one respondents considered existing facilities or waterways underneath the bridges as the reason for selecting closed deck drains. Twenty-six respondents preferred drains that are hung on the exterior of columns compared to eighteen respondents who preferred embedded closed systems. While the outlet location is the dominant reason for selecting the hung-on-the-exterior closed system, aesthetics are the main reason for using an embedded closed system. The survey participants provided a few additional reasons (beyond the alternatives in the survey) for selecting hung-on-the-exterior systems: ease of replacement and repairs, installation after bridge construction, lower risk (rupture easily detected), and ease of maintenance or replacement of inlets or pipes after clogging. The only additional reason mentioned by a participant for using embedded systems was reduced life cycle costs. The design of grate inlets and increase of pipe size are the top priority for improving the bridge deck drain design. Respondents mentioned other priorities for improving bridge deck drains designs. These priorities are listed at the bottom of Figure 3.5. They include standardization of bridge deck drain design and lowering maintenance costs through proper design.

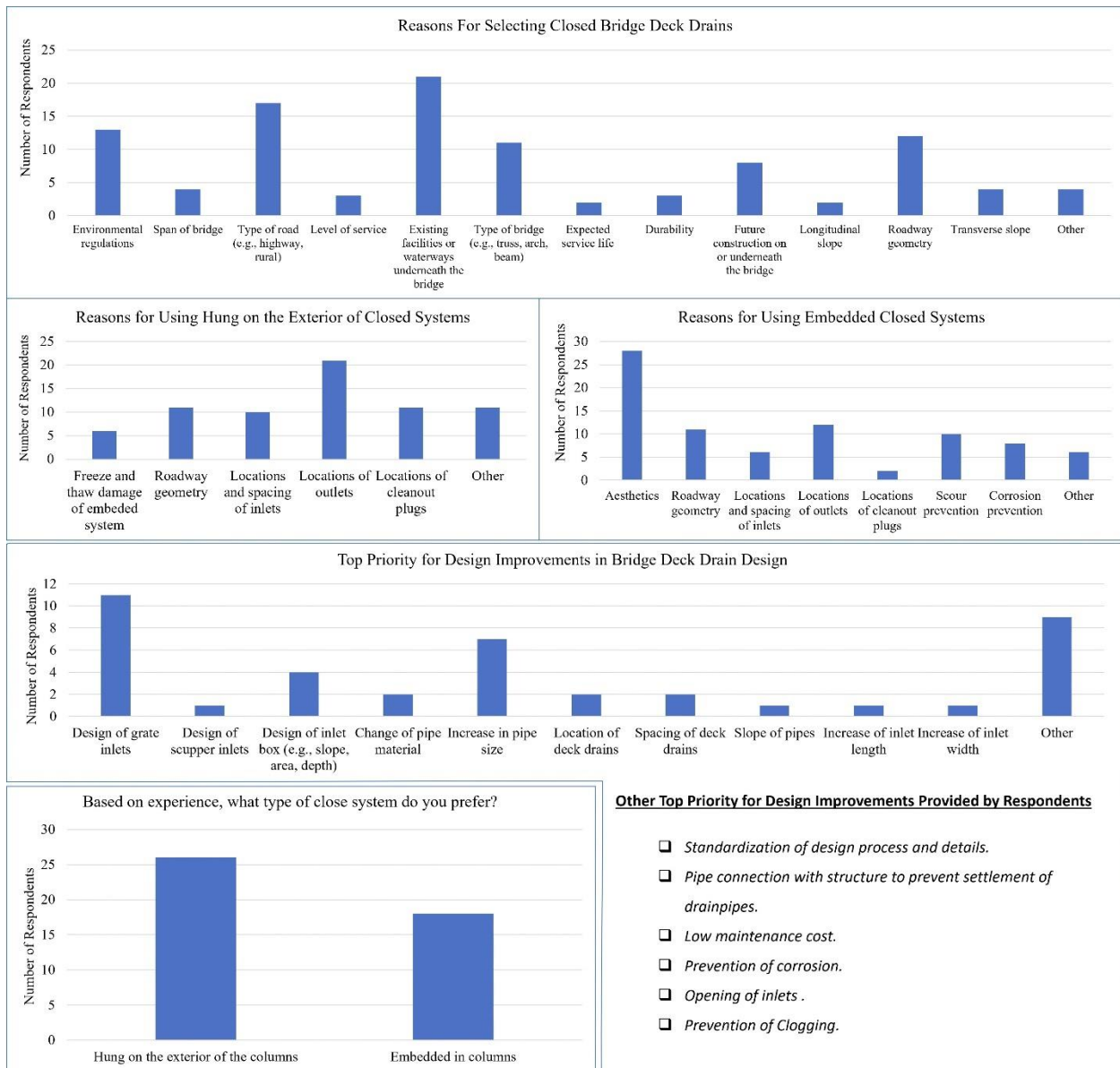


Figure 3.5 Summary of survey responses on bridge deck drain design (Texas)

The last question in the design section asked for recommendations to improve the designs of bridge deck drains. The recommendations from the respondents are summarized below:

- Design drains to have easy maintenance access for lower maintenance costs and higher service life.
- Standardize the design and detailing of closed bridge deck drains.
 - Two engineers may draft different details and drawings.

- Generally, the drawn details are unclear, and poor drain performance can be partially due to how drawings are drafted.
- Develop a design method to calculate the capacity, flow, size, and spacing for the drainpipes at inlets and outlet locations.
- Use more embedded drains for aesthetic reasons.
- Use more robust, non-corrosive materials.
- Use inlets with higher capacities and conveyance.
- Design drains to achieve self-cleansing velocities.

Out-of-State Results

The dominant reasons for selecting closed systems are existing facilities below the bridge and environmental regulations (Figure 3.6). Embedded systems are used mainly because of aesthetics. Three respondents from Tennessee, New Hampshire, and North Dakota mentioned that they do not use embedded bridge deck drains. Locations and spacing of inlets are the dominant reason for selecting hung-on-the-exterior closed systems. Other respondents mentioned that hung systems are used because they are easier to install and maintain than embedded systems. The top three priorities for design improvements include improvements in the design of scupper and grate inlets, the design of inlet boxes, and the location and spacing of bridge deck drains. One respondent from North Carolina recommends that bridge deck drains stop being used. Twenty-eight respondents prefer hung systems to embedded systems, while only four respondents prefer embedded systems.



Figure 3.6 Summary of survey responses on bridge deck drain design (outside Texas)

Polyvinyl Chloride (PVC) is the most common pipe material used for bridge deck drains, as shown in Figure 3.7. The other pipe materials used are steel, fiberglass, and ductile iron. One participant from New Hampshire mentioned that they use Fiberglass Reinforced Plastic (FRP) pipes for bridge deck drains.

Bridge Deck Drain Pipes		CO	FL	KS	LA	ME	MI	MN	NE	NJ	NY
Pipe Material	PVC	✓	✓						✓	✓	✓
	Fiberglass	✓		✓		✓					
	Ductile Iron	✓					✓				✓
	Steel				✓			✓			

Bridge Deck Drain Pipes		NC	ND	OK	OR	ON CANADA	PA	SC	TN	VA	WA
Pipe Material	PVC	✓	✓			✓		✓	✓	✓	
	Fiberglass						✓	✓			
	Ductile Iron									✓	✓
	Steel		✓	✓	✓		✓				

Figure 3.7 Pipe materials used for bridge deck drains acquired from the survey (outside Texas)

The top three reasons for selecting PVC pipes are resistant to corrosion, lightweight, and ease of installation. Steel pipes are used for their durability and resistance to corrosion when galvanized. A respondent from Louisiana said Louisiana uses steel pipes for their strength. Ductile iron also offers durability and has low maintenance requirements. Fiberglass is used because of its low maintenance requirements and its corrosion-resistant properties.

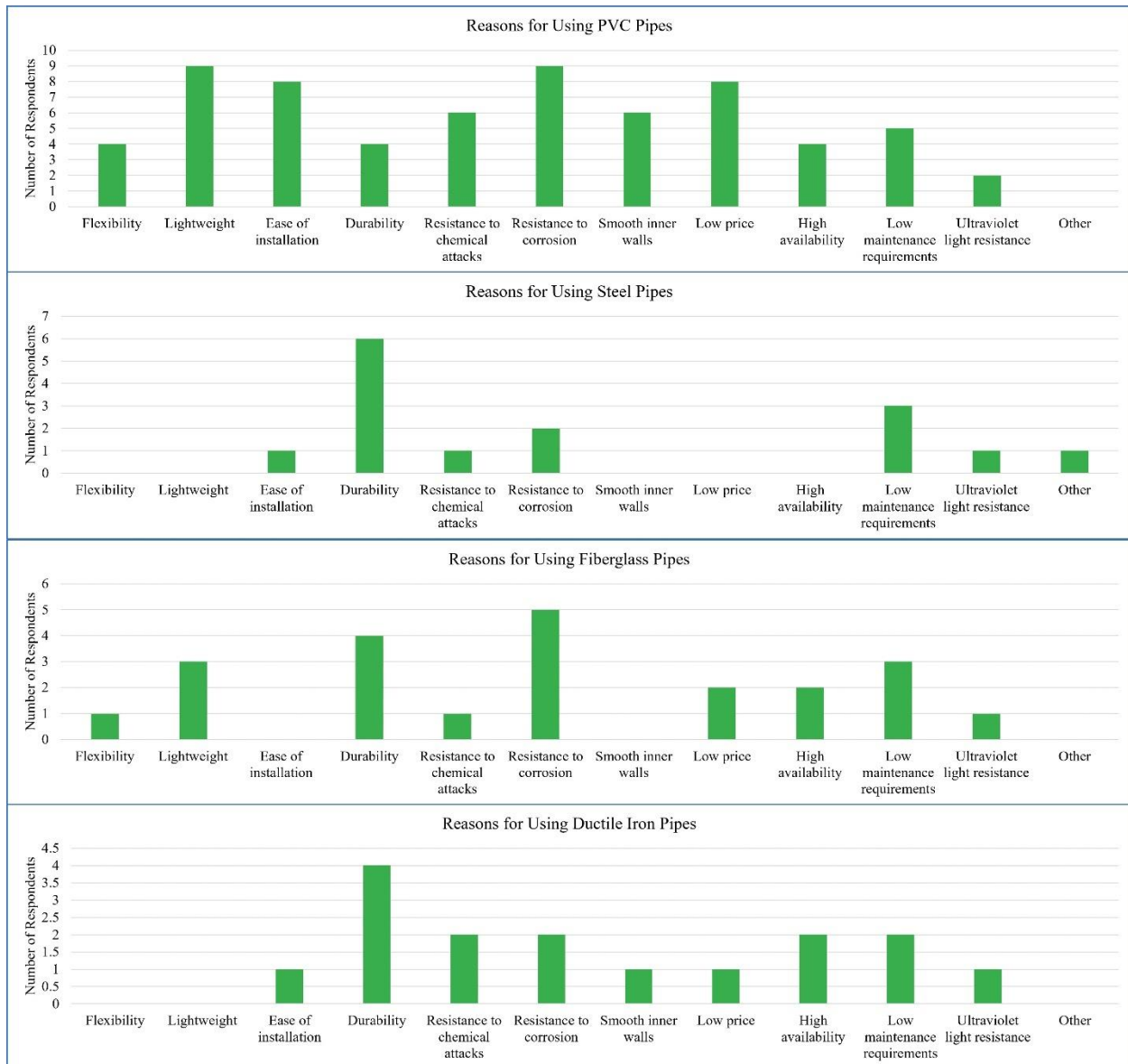


Figure 3.8 Reasons for selecting pipe materials (outside Texas)

After submitting the reasons for selecting the different pipe materials, the participants were asked about the common problems observed with their selected pipe materials. Figure 3.9 summarizes the common problems of drainpipes. The New Hampshire respondent that said FRP pipes are used for bridge deck drains mentioned that the price of FRP pipes is the main issue with this material.

PVC	Fiberglass	Ductile Iron	Steel
<ul style="list-style-type: none"> • Connections • Cracking • Durability • Water hammer • Aging • Clogging • Vandalism • UV damage • Joints • Reaction to water forces • Freeze and thaw cracks • Joints can leak 	<ul style="list-style-type: none"> • Durability of fittings and joints • Cracks and breaks easier than other types 	<ul style="list-style-type: none"> • Corrosion • Cracking • Connection failures • Heavy weight (difficult installation) 	<ul style="list-style-type: none"> • Corrosion (includes galvanized steel) • Clogging (plugs up) • Cleanouts seize over time • Surface rust discolors the concrete

Figure 3.9 Common problems with bridge deck drainpipes (outside Texas)

The participants were also asked for recommendations to improve the service life of bridge deck drains. The results are listed below:

- Eliminate the use of bridge deck drains.
 - They capture less runoff than what they are designed for.
 - The means to allow overflow in larger events should be considered.
 - Hung and exposed systems need to be eliminated.
- Make maintenance access easier and create a better maintenance routine.
- Use a more defined interface between structural design preferences for deck drain location and performance and hydraulic preferences.
- Incorporate stormwater treatment into the drain system.
- Restrict bypass flow at each bridge-end collector (catch basin or flume off the bridge).
- Use vertical pipes through openings instead of grate inlets.
- Use curb opening style inlets with improved throats.
- Design scuppers to be self-cleansing.
 - Pressure washing twice a year.

- Inlets readily collect dirt and debris, and weed starts growing on them.
- Improve shoulder width.
 - AASHTO allows for flexibility in shoulder width on long-spanned bridges.
- Remove the 90° turn at inlets.
 - Causes pipes to clog.

The last question in the design section of the out-of-state survey asked about innovative systems and designs of bridge deck drains. The recommendations from the respondents are summarized below:

- Use fiberglass-reinforced plastic (FRP) pipes.
- Use FRP scuppers and downspouts for durability.
- Consider an open “trough” type design to capture small flows.
 - Larger flows can overflow.
- Increase frequency of cleanout inspections.
- To the extent practicable, use slotted connections that allow overflow if the systems get overwhelmed.

3.3.4 Bridge Deck Drain Construction

In-State Results

The construction section consisted of two questions that inquired about:

- Practices that negatively impact the performance or service life of drains.
- Recommendations for improving the installation of drains.

The practices that were found to negatively impact the performance or service life of bridge deck drains are:

- Lack of inspections
- Improper design of pipe hangers and pipe expansion joints.
- Change of grade and alignment without engineers’ approval.
- Improper installation of inlets by contractors according to the plans.

- Use of PVC for pipe runs.
- Difficulty accessing cleanouts.
- Use of small diameter pipes.
- Too many bends.
- Failure of weak hangers that creates hanging drains.
- Hanger corrosion.
- Design of unsupported joints.

Recommendations for improving the construction and installation of bridge deck drains are summarized below:

- Designers need to pay more attention to drains, support, and expansion joints.
 - A lot of details are usually left for contractors.
- Inspection documentation should be added to the site manager sampling and testing requirements.
- Vegetation growth at the outlet must be considered.
- Supports for hung systems need to be improved.
- All sag points must have drain slots.
- Post-construction inspection should be performed to check if any sag points are created accidentally.
- A waffle-type opening at the deck drain could be helpful.
 - Prevents many types of debris from entering and clogging the pipes (e.g., 20 oz. water bottles).
- Standard designs with good and clear details must be developed.
- Durable materials need to be specified, and ample capacity for significant rainfall events needs to be provided.
- Robust inlets and grates should be used to prevent the infiltration of large materials that tend to clog the systems.

Out-of-State Results

The practices that were found to negatively impact the performance or service life of bridge deck drains are:

- Not cleaning out construction debris.
- Not extending drains below bridge decks.
- Not constructing at the correct slope or other design specifications.
- Not sealing correctly around the drains.
- Using materials that corrode (including galvanized steel).
- Using inappropriate connections.
- Using improperly constructed supports.
- Finishing work around the inlets improperly.
- Resurfacing decks improperly. That often affects the inlet flow performance negatively by changing the pavement depth to be exact.
- Setting grates against barriers improperly.
- Pouring concrete in embedded drains during the column pour.
 - Makes the drain unusable, so an external drain must be installed.
- Difficulty of cleaning embedded closed systems.

Recommendations for improving the construction and installation of bridge deck drains from the out-of-state survey are summarized below:

- Follow specifications.
- Use proper materials.
- Improve scupper designs.
- Use better details and inspection methods (they are not typical plumbing systems).
- Use exact coordinate tables in the plan set.
- Make sure space is small between grate inlets and curbs/barriers.
- Minimize the number of bends.
- Increase pipe slope, if possible.

3.3.5 Bridge Deck Drain Maintenance & Inspection

In-State Results

Figure 3.10 shows that TxDOT is the primary authority for bridge deck drain maintenance. A respondent mentioned that the agency maintains the drains with the help of consultants. Routine inspection is the most common inspection type for bridge deck drains. The method and schedule of maintenance highly depend on inspection recommendations, followed by observed performance and customer complaints. One respondent stated that no maintenance is scheduled.

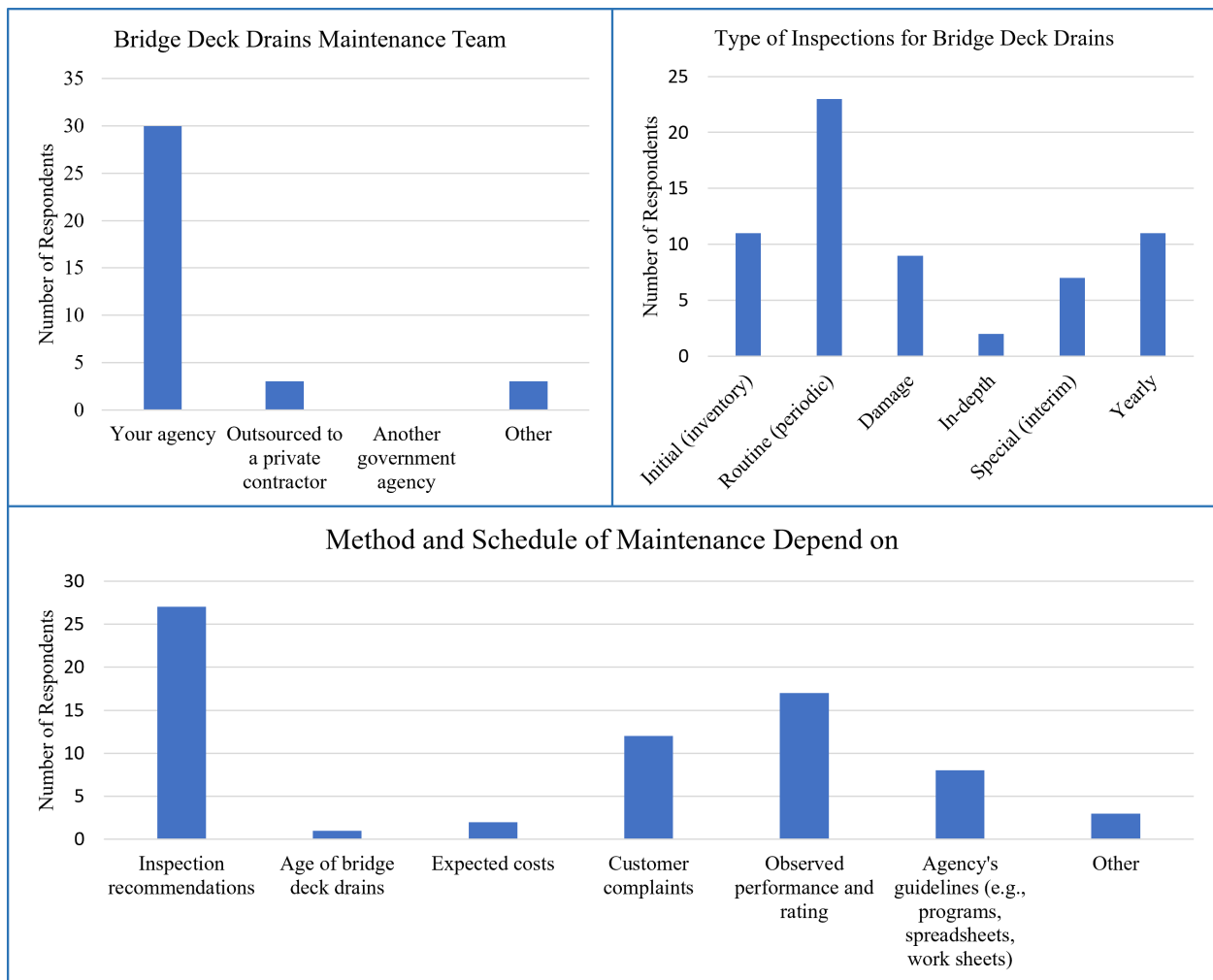


Figure 3.10 Bridge deck drains inspection and maintenance (Texas)

Figure 3.11 shows the most common methods for cleaning and maintaining bridge deck drains. The commonly used methods in Texas for cleaning bridge deck drains are hand or hand tools, followed by flushing using low-pressure, high-volume water, and high-pressure power washers. The most common maintenance approach is regular preventative maintenance because closed systems require it frequently. Most bridges in Texas drain the runoff to the soil right below the bridges.

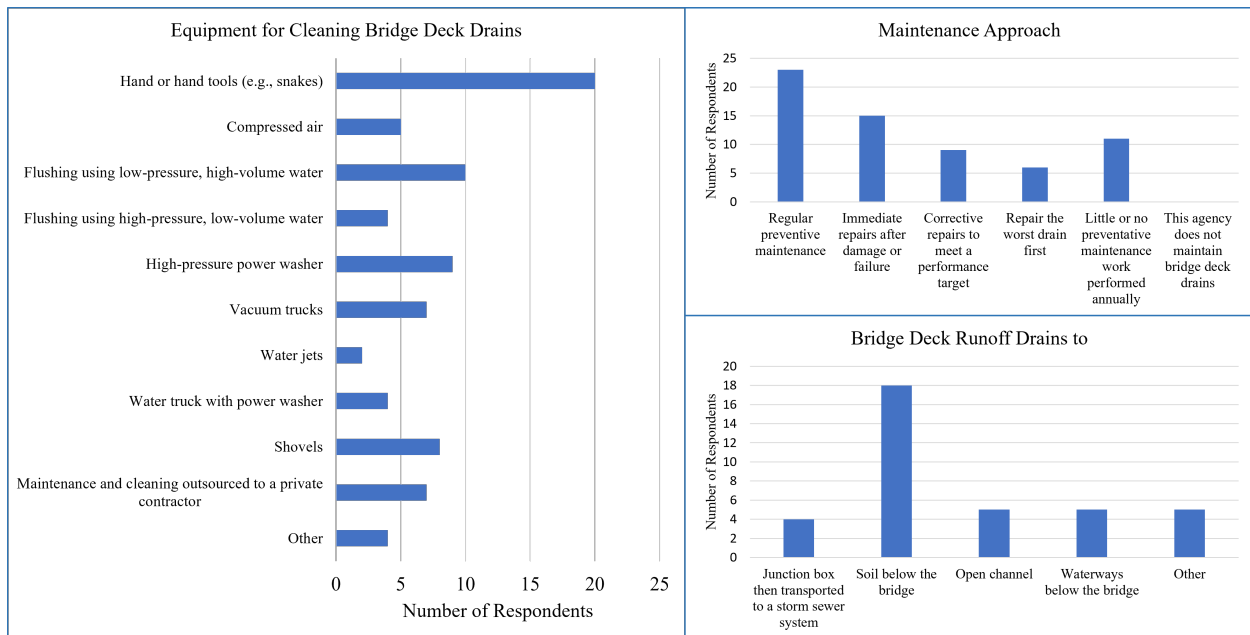


Figure 3.11 Cleaning equipment, maintenance approach, and runoff end location (Texas)

The maintenance and inspection section also consisted of a question inquiring about available inventory data for bridge deck drains. Figure 3.12 shows the commonly collected inventory data in Texas. The commonly available inventory data include inspection dates, photographs, and existing conditions of bridge deck drains. A participant stated that drains are rarely considered during bridge inspections. It seems that tracking the performance and maintenance of bridge deck drains is currently difficult since nine respondents mentioned that no inventory exists!

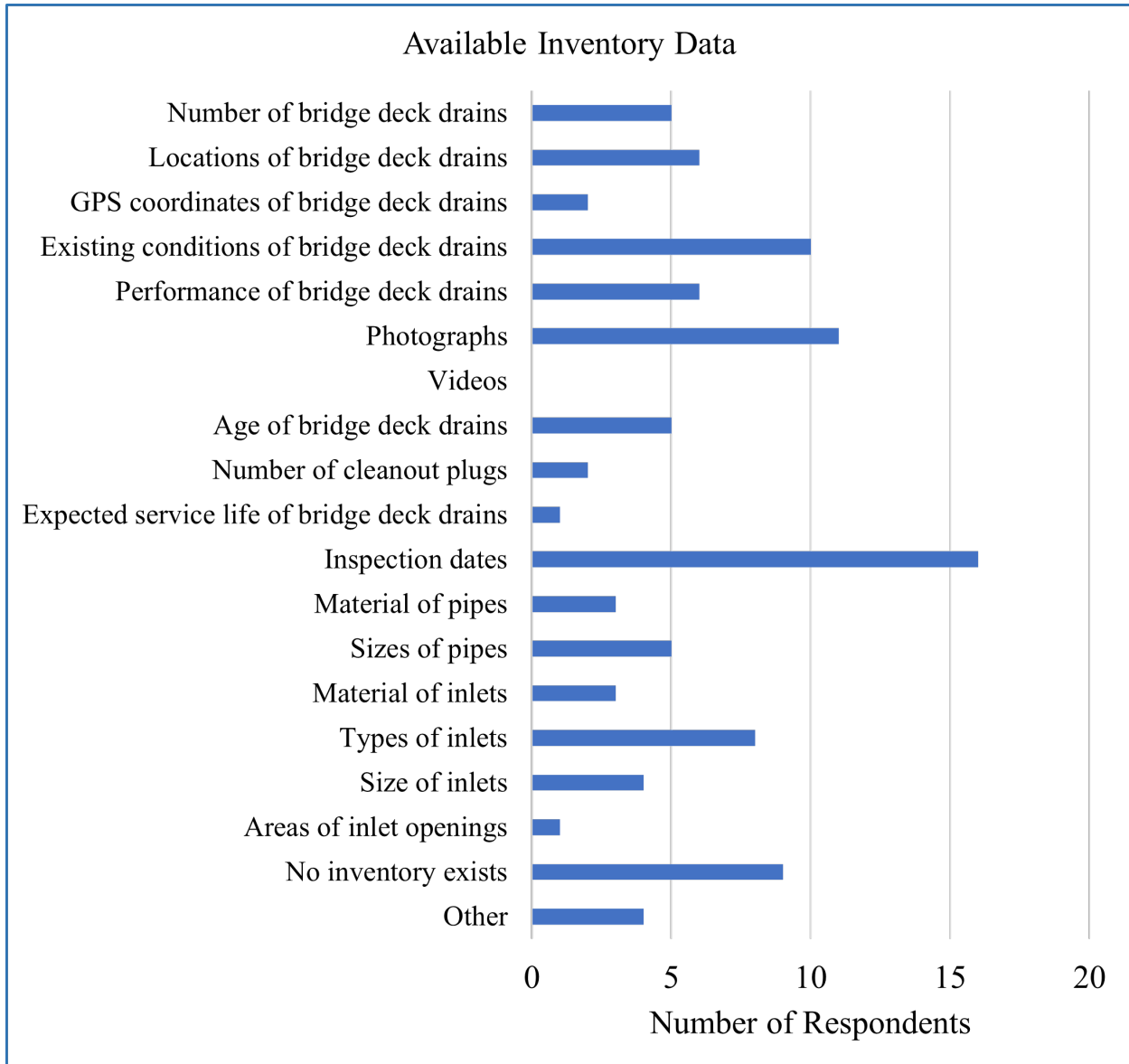


Figure 3.12 Available inventory data on bridge deck drains (Texas)

Figure 3.13 shows the recommendations for improving service life and the methods for determining where drains are in their service life. Conducting regular preventative maintenance, increasing the number of cleanout plugs, and placing drains conscientiously were the highest chosen recommendations for improving service life. Visual inspection is the most common method for determining where drains are in their service life.

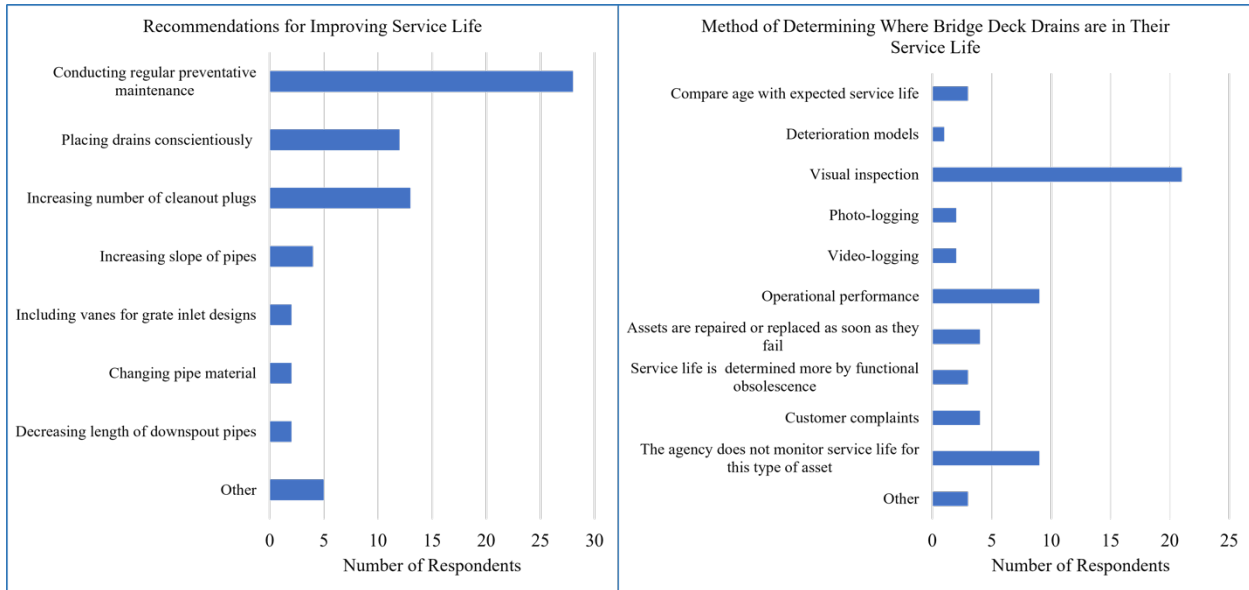


Figure 3.13 Recommendations for improving service life (Left) and determining where drains are in their service life (Right) (Texas)

Out-of-State Results

Most Department of Transportations are the parties responsible for bridge deck drain maintenance in their states (Figure 3.14). Routine inspections are the most common type of inspection for bridge deck drains because they tend to clog. The method and schedule of maintenance in most states depend on inspection recommendations. Customer complaints, observed performance, and agencies’ guidelines also help in scheduling maintenance.

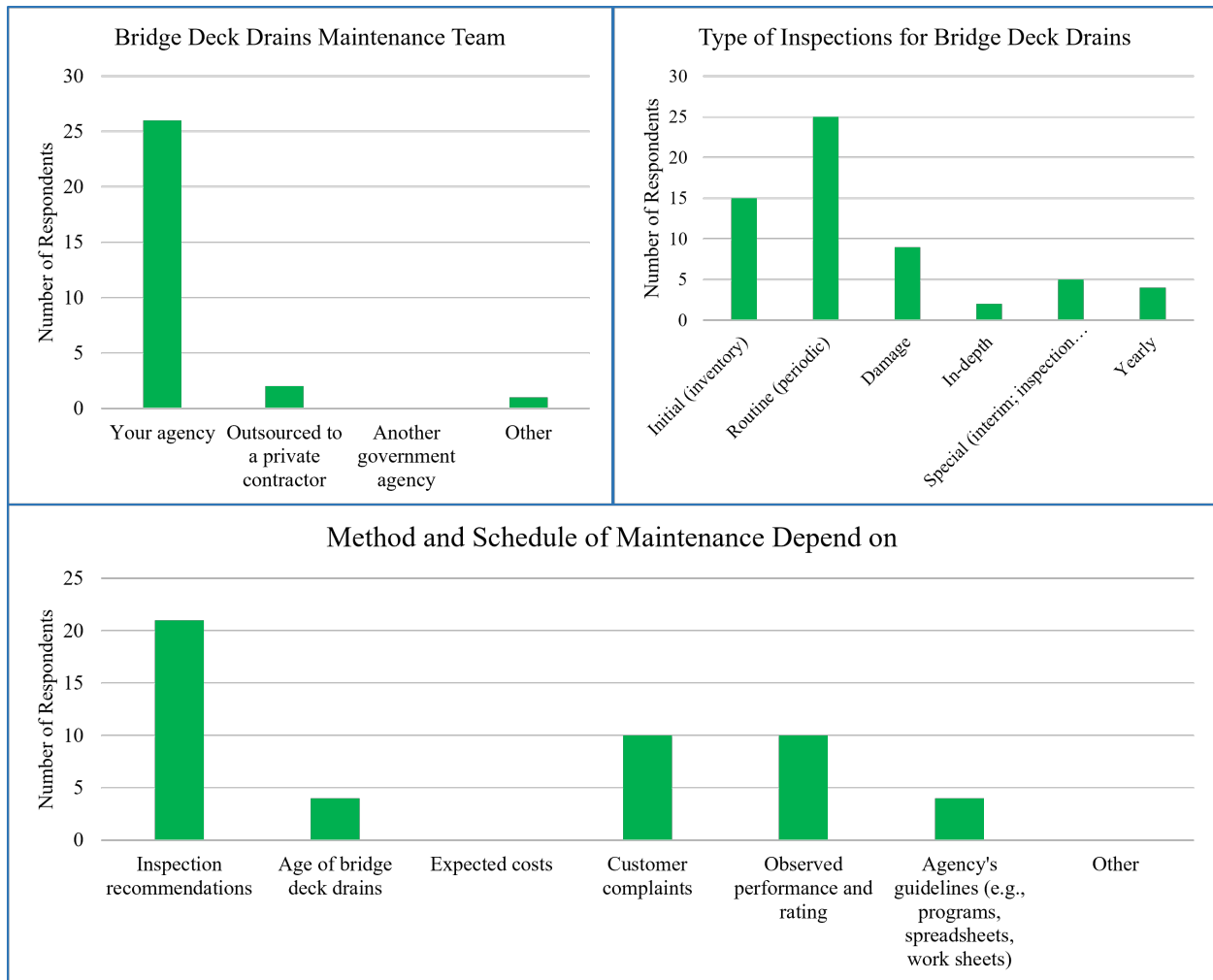


Figure 3.14 Bridge deck drains inspection and maintenance (outside Texas)

The most common cleaning method is hand or hand tools because clogging of inlets is the most recurring issue from the results. Flushing with low-pressure, high-volume water and washing using a high-pressure power washer are also common in the other states (Figure 3.15). While regular preventive maintenance is the most common maintenance approach (twelve respondents), little or no preventative maintenance is the second highly selected alternative. Most bridges in the states drain the runoff to the soil below the bridge. One respondent said that runoff is typically drained to stormwater systems.

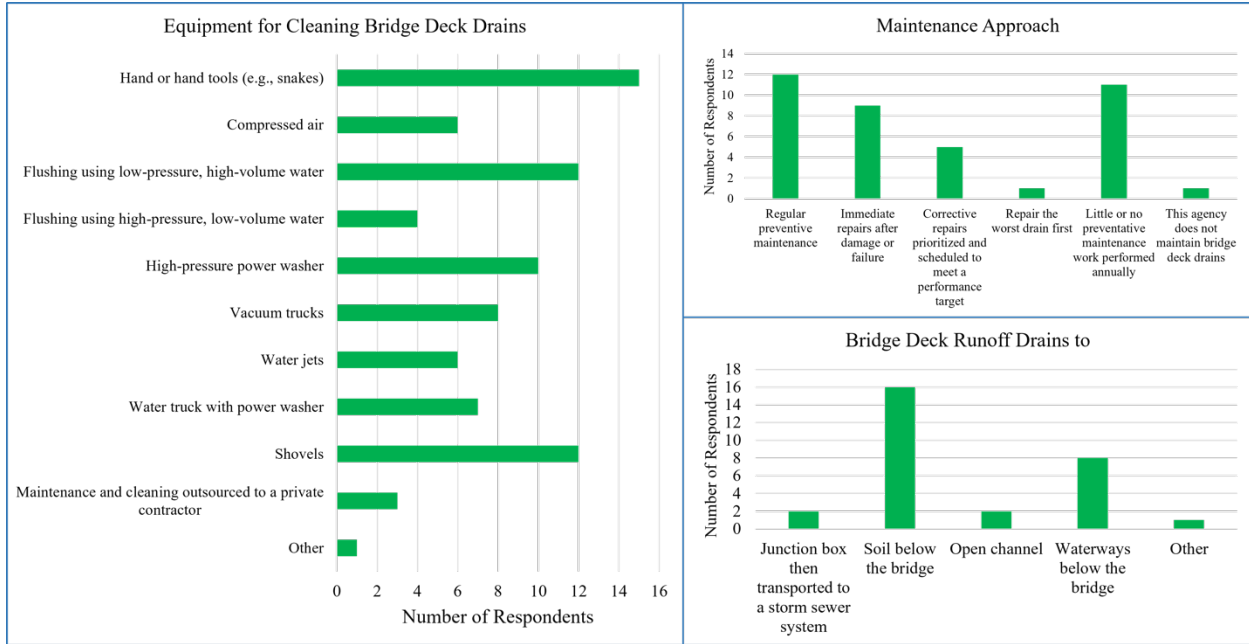


Figure 3.15 Cleaning equipment, maintenance approach, and runoff end location (outside Texas)

Figure 3.16 displays the most commonly collected inventory data on bridge deck drains. The most common available inventory data are photographs and existing conditions of drains. Eleven respondents claimed no inventory data exists!

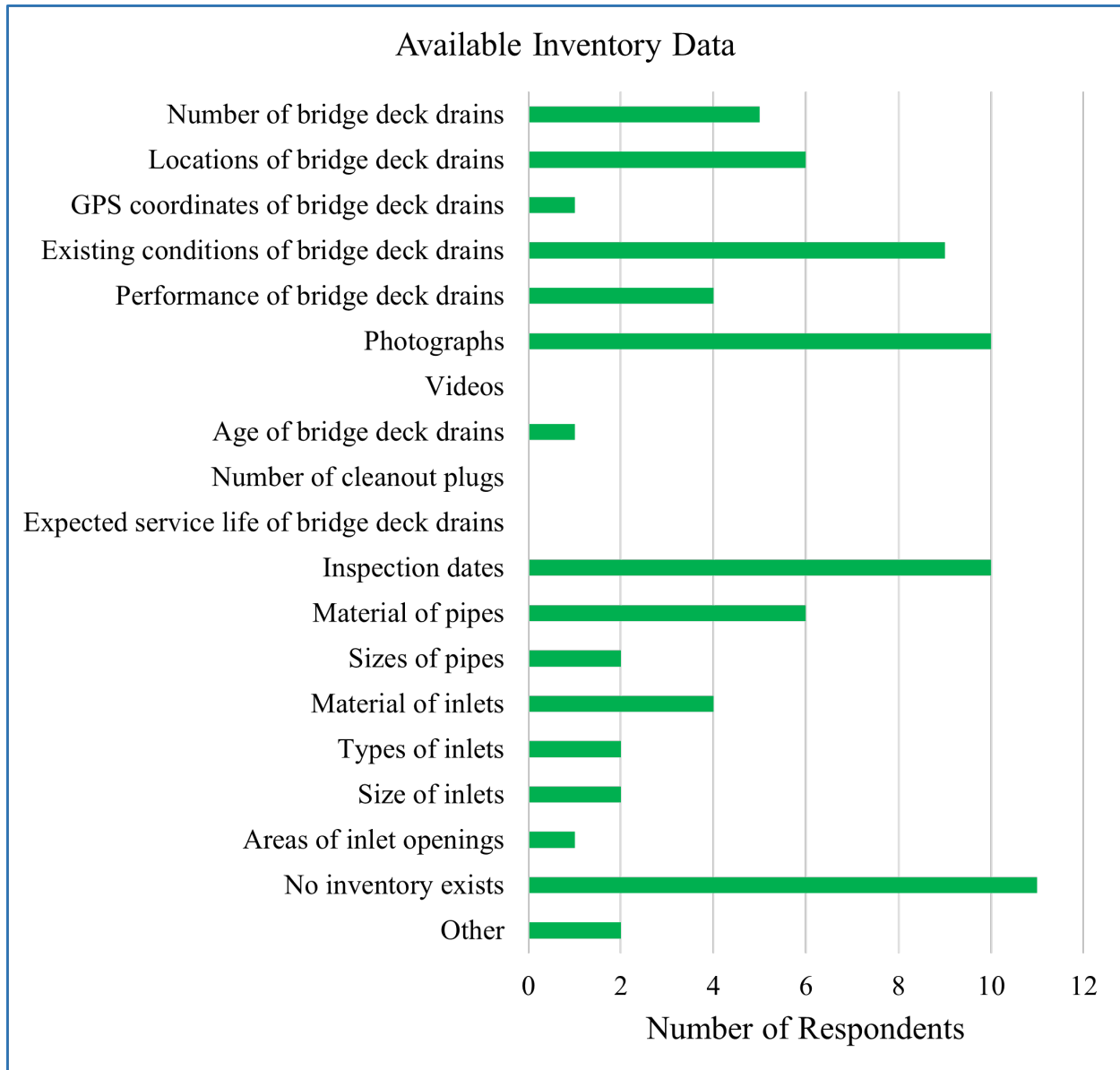


Figure 3.16 Available inventory data on bridge deck drains (outside Texas)

The most selected recommendation for improving the service life of bridge deck drains is regular preventative maintenance. This recommendation scored highest in both surveys (Figure 3.13 and Figure 3.17). Increasing the slope of pipes and placing drains conscientiously are also essential recommendations. Some respondents recommended increasing shoulder width to allow for higher spread and increase drain spacing. Visual inspection is the most common method for determining bridge deck drains' status in their service life.

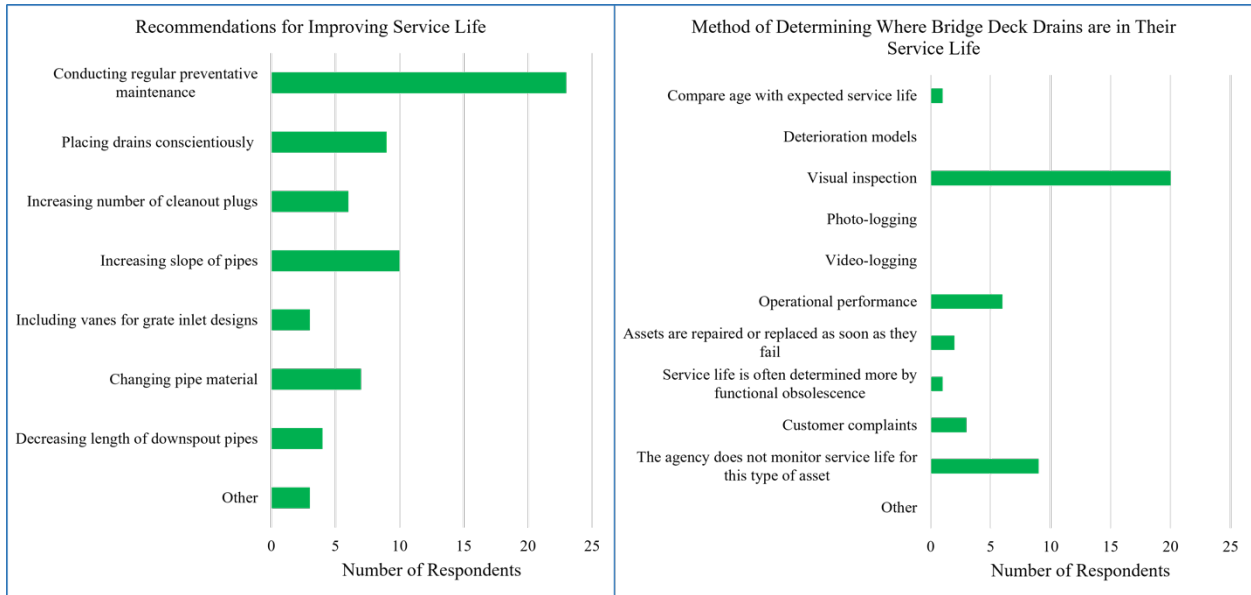


Figure 3.17 Recommendations for improving service life (Left) and determining where drains are in their service life (Right) (outside Texas)

3.3.6 Follow-Up Interviews

Figure 3.18 displays the number of participants who are willing to participate in follow-up interviews. Nine participants from Texas showed interest in participating in follow-up interviews. They are located in eight districts: Atlanta, Austin, Beaumont, Dallas, El Paso, Houston, Lufkin, and Pharr. Thirteen participants outside Texas showed interest in participating in follow-up interviews. They are located in nine states: Colorado, Louisiana, Maine, Michigan, Nebraska, North Carolina, Pennsylvania, Tennessee, and Virginia.



Figure 3.18 Follow-up interviews

CHAPTER 4 - FOLLOW-UP INTERVIEWS

The research team conducted follow-up interviews with selected survey participants to identify recommendations for bridge deck drain design, construction, and maintenance. These interviews were aimed to identify best practices and lessons learned. Selection of interviewees, instructions for conducting interviews, interview questions, and interview results are presented in this report.

4.1 Selection of Interviewees

The research team considered the following criteria to choose interviewees:

- Selecting individuals that are willing to participate in the follow-up interviews.
- Selecting respondents that provided the most detailed information in their survey responses.
- Selecting individuals from TxDOT districts experienced with bridge deck drains.

Based on these criteria, the research team has conducted interviews with participants from NCDOT and five TxDOT districts:

Austin, Beaumont, Dallas, Houston, and Lufkin.

4.2 Instructions for Conducting Follow-Up Interviews

To conduct follow-up interviews with the selected interviewees, the sessions were structured based on the four following tasks:

1. Reviewing contact information.
2. Reviewing survey responses and asking whether respondents would like to further explain their responses.
3. Acquiring more detailed information about bridge deck drains.
4. Obtaining recommendations to improve the design, construction, and maintenance of bridge deck drains.

4.3 Interview Questions

The research team created the interview questions based on the literature review and survey results. The questions were designed to acquire missing information that has not been obtained from the surveys or literature. The interview questions are structured similarly to the survey questionnaires. The questions are divided into four sections: failure, design, construction, and maintenance and inspection.

4.3.1 Failure Questions

1. According to the results of both surveys, the most common problem with bridge deck drains is the clogging of inlets.
 - a. Do you agree?
 - b. Do you have any recommendations about inlet designs, maintenance, and construction to prevent the failures of bridge deck drains?
2. Based on the results of both surveys, the second most common problem with bridge deck drains is the clogging of pipes due to bends.
 - a. Do you agree?
 - b. Are there methods or designs for bridge deck drains that prevent debris from clogging the pipes? (Preventing debris from entering through inlets or letting debris pass through the system without causing frequent clogging).
3. According to the out-of-state survey, the third most common problem is pipes clogging due to insufficient pipe diameter. TxDOT typically uses 8" diameter pipes for closed systems. Should TxDOT start using larger diameter pipes?
4. FHWA recommends that the slope of pipes be 8%, but the minimum permissible value is 2%, as most states recommend. TxDOT typically uses 3% as the slope of pipes. Should TxDOT increase the minimum slope requirement for pipes?

4.3.2 Design Questions

5. According to the TxDOT survey, the second top reason for choosing closed bridge deck drains was the type of road.
 - a. How would the type of road impacts TxDOT's decisions to use closed bridge deck drains?
 - b. Do you have any recommendations for the type of closed system that should be used based on the type of road?
 - c. Do you have any recommendations for using open systems instead of closed systems on different road types?

6. For the two types of closed bridge deck drains (Embedded in columns and hung on bridge exterior), both survey results (TxDOT and out-of-state) showed that hung systems are preferred to embedded systems. Responses of the two surveys also showed that the dominant reason for selecting embedded systems was aesthetics.
 - a. Are there any recommendations for making hung systems more aesthetically pleasing?
 - b. If aesthetics were not an issue, would you only use hung bridge deck drains for closed systems?

7. According to the out-of-state survey, the top priorities for design improvements are the design of scupper inlets, design of inlet boxes, and determination of locations and spacings of bridge deck drains. Should a new design method require agencies to add more drains (decrease drain spacing) for capturing runoff effectively?

4.3.3 Construction Questions

8. Several survey respondents pointed out that contractors construct and install drains improperly. Contractors can make grade changes without the engineer's approval or sometimes neglect cleaning the construction debris, affecting the system's performance.
 - a. Do you agree?
 - b. What do you recommend to alleviate this problem?

4.3.4 Maintenance and Inspection Questions

9. The top recommendation for improving bridge deck drains' service life in both surveys was conducting regular preventative maintenance. How many times a year should there be a routine inspection and regular preventive maintenance?
10. Various methods and tools have been used for cleaning bridge deck drains (e.g., flushing, compressed air, power washers). Which cleaning method do you recommend?
11. Some respondents mentioned that there are available inventory data on bridge deck drains (e.g., inspection dates, photographs, number of cleanout plugs), but according to others, no inventory exists.
 - a. What information do you collect on bridge deck drains?
 - b. Do you have an asset management system for tracking inspections, cleaning, maintenance, and performance of bridge deck drains?
 - c. If you do not have an asset management system, do you recommend having an asset management system for collecting and archiving data and spatial information in an inventory?
12. Finally, do you have any other recommendations to improve bridge deck drains?

4.4 Interview Results

The research team has conducted interviews with one respondent from NCDOT and 5 TxDOT respondents from Austin, Beaumont, Dallas, Houston, and Lufkin. These interviews were aimed to identify the current practices, prevailing problems, and suggested improvements for bridge deck drains. Summaries of the interviews are presented in this section.

4.4.1 Interviewee Number 1 (Austin, TxDOT)

Failure of Bridge Deck Drains

Common Problems

- Clogging often occurs at bends with no cleanouts. Therefore, it is recommended to provide cleanouts at all bends.
- The clogging issue is holistic and not component-specific.
- If bridge deck drains do not work properly, water leaks to other bridge components. Leaking water can reach other locations, such as expansion joints. Water can drain from an improperly maintained expansion joint to the top of the bent cap. Over time, stains can be observed on the bent cap and could end up forming cracks.

Clogging of Pipes

- Clogging of pipes happens at specific pipe locations.
- Pipes are problematic because they often need to be bent 90°.
- Cleanouts need to be provided above all bends.
- Cleaning is simple where cleanouts exist because debris accumulates at bends.
- If locations of cleanouts are correctly designed, regular maintenance help ensure systems' performance.
- Regular inspection (and perhaps maintenance) of pipes near bends is recommended.

Diameter of Pipes

- It is not necessarily needed to increase pipe size. The pipe diameters and inlet spacings should be designed based on hydraulic principles. If inlet spacing is designed properly, 8” pipes could be adequate.

Slope of Pipes

- Reaching self-cleansing velocities in pipes is recommended.
- The velocities in pipes need to be hydraulically designed.
- The bridge grades dictate slopes of pipes. It is recommended for pipes to be at least above the bottom of the girder.

Design of Bridge Deck Drains

Type of Closed Systems

- The drainage system must go through the bent cap and into the ground if a roadway exists below the bridge.
- Closed systems go through the bent cap on highway systems.
 - Pipes go through the hammerhead.
 - Pipes are drained through outlets located in columns.
- Clogging occurs if cleanouts are not provided at the bends near bent caps.
- It is recommended to provide enough cleanouts when designing drains. Placing cleanouts at their proper locations is recommended.

Hung Systems

- The application of hung systems depends on bridge locations. Hung systems are often used at places near creeks and rivers. Hung systems should not be used in urban areas.
- Generally, maintenance is much easier for hung systems.
- Hung systems are preferred to embedded systems. If a roadway exists below the bridge, hung systems may still be used if kept away from the roadside limit.

Spacing of Drains

- Capturing runoff before reaching expansion joints is essential. Because if expansion joints fail to drain water, the water goes from the joint to the bent cap and stains the bent cap.
- For all bridges, it is recommended for TxDOT to specify the bridge deck drains in detail.
- TxDOT should enforce contractors to place drains exactly where they are designed to be located on all bridges. Enforcement is not done on all bridges. For smaller bridges, the contractor is provided with only a one-sheet instruction that is not adequate.

Construction of Bridge Deck Drains

Construction

- It is recommended to find the source of each problem (contractor, designer, inspector) before taking any corrective actions.

Maintenance and Inspection of Bridge Deck Drains

Maintenance Frequency

- Maintenance is recommended once every five years, even if no issues are found.
- The frequency of maintenance should increase in places with sand, gravel, debris, litter, and places known for having sandstorm occurrences. At least once every three years is recommended as the maintenance frequency in these places.

Assets and Inventory Data

- TxDOT inspects bridges every two years. The inspection sheet has a column for drainage systems. But it does not seem to be adequate.
- It is recommended to fully document the existence and performance of bridge deck drains.
- It is recommended to have a detailed deck drain section in the bridge asset management system.
- The conditions of drains are easy to record based on visual inspections.
- Drains do not necessarily need models for finding the service life and scheduling maintenance.

General Comments

- It is recommended for TxDOT to evaluate and document the conditions of bridge deck drains.
- It is recommended to provide detailed designs of bridge deck drains for contractors. Enforcement of the detailed designs through inspections is essential.
- Based on the area engineer's experience, existing poor drains should be identified and inspected.
- It is recommended to monitor and evaluate the drains on young bridges. Corrective actions should be taken if any issues are found.
- Designers need to be aware of when they can substitute the drainage systems with curb openings.
 - Openings through barrier curbs can sometimes substitute the use of bridge deck drains in Texas.

4.4.2 Interviewee Number 2 (Houston, TxDOT)

Failure of Bridge Deck Drains

Common Problems

- Inlets are usually clogged. Clogging of inlets can often be solved through power washing.
- It is challenging to deal with the high amount of traffic on freeways.
- It is challenging to close a bridge or a lane long enough for cleaning deck drains. It is especially challenging on freeways with heavy traffic.
 - Traffic control is expensive.
- Resources will not be spent on clogged inlets until their conditions are measured.
- Auditing and having an inspection record that contains information about the clogging of inlets is recommended.

Clogging of Pipes

- Cleanouts help counter clogging in pipes.
- It is recommended to use a T-connection with a cleanout on one side to remove clogging.

Diameter of Pipes

- TxDOT switched to a bigger pipe size (8") based on the hydraulics team request. But there is a tradeoff here. Structurally, smaller pipes are preferred. Hydraulically, larger pipes are needed. Detailed design of deck drains is recommended to size pipes properly.

Slope of Pipes

- It is difficult to have an adequate slope when scuppers are placed in the middle of spans.
- It is challenging to place inlets where low points exist in the middle of spans.
- Placing inlets at the exact locations shown on the plans is recommended.
- There should be enough space for pipes to be sloped to prevent pipes from controlling the vertical clearance. Not enough space is often provided for pipes to have higher slopes.

Design of Bridge Deck Drains

Type of Closed Systems

- There are no guidelines that specify which type of system should be used on which type of road.
- Closed systems are used to avoid polluting waterways below bridges.

Hung Systems

- It is recommended to place drains on the sides of columns that drivers cannot see.

Spacing of Drains

- Adjusting the hydraulic requirements to put the inlets at the bents is recommended. The bent is the best place to drain water from.
- Inlets placed in the middle of spans are difficult to drain.
- Limiting ponding to the shoulder only requires more closely spaced drains.
- Allowing ponding width to reach the first lane decreases the number of drains needed.
- Detailed design of closed systems is recommended for all bridges that require closed systems.

- It is recommended for TxDOT to have detailed guidelines for designing all bridge deck drains.

Construction of Bridge Deck Drains

Construction

- The construction of embedded systems is challenging.
- Contractors and inspectors may face difficulties if drawings are not detailed.
- Feedback on drawings from the job site during construction is recommended.

Maintenance and Inspection of Bridge Deck Drains

Maintenance Frequency

- Inlet conditions should be inspected during bridge inspections performed every 24 months.
- Clogging of inlets is recorded as notes that do not affect the bridge ratings. Therefore, these notes about clogged inlets may be ignored.
- It is recommended to document the number of drains and how many of those drains are clogged.
- Pouring water down the drains (possibly through flushing) to observe systems' performance is recommended.

Assets and Inventory Data

- Documentation of inlet conditions can be done by walking on the shoulder along the bridge deck and marking on a sketch of the deck with inlets are clogged.
- Documenting while walking on the shoulder does not require traffic control.
- An asset management system for bridge deck drains is better kept separate from the bridge's asset management system.
 - Bridge inventory inspections are regulated at a federal level.
 - Only certain certified individuals can conduct bridge inventory inspections.
 - Inspections of bridge deck drains could be easier if bridge deck drains were separated from the national bridge inventory.
 - Having an online inspection system is recommended.

General Comments

- If embedded PVC pipes are proven to be inadequate, TxDOT should consider using Chlorinated PolyVinyl Chloride (CPVC) instead.
 - Concrete heat of hydration is produced during concrete curing. This reaction is exothermic. This heat could damage the PVC pipes since PVC deteriorates at reasonably low temperatures (140F).
 - It is possible to run a scope inside the columns to check for cracks on PVC pipes.
 - It is likely that embedded PVC pipes do not supply the required 75 years of service life.
- PVC could crack if used at expansion joints. Flexible PVC should be considered at expansion joints.

4.4.3 Interviewee Number 3 (Dallas, TxDOT)

Failure of Bridge Deck Drains

Common Problems

- Drain off the side of the bridge when permissible. Draining through the side is done through slotted rails.
- It is recommended to avoid using bridge deck drains when possible. Limiting the number of drains is recommended.
- It is impossible to drain off the side of the bridge when railroads or roadways exist below the bridge. Closed systems must be used if railroads or roadways exist below bridges.
- Clogging of inlets is one of the main problems with bridge deck drains.
- Grates clog, break, and get stolen.
- External PVC pipes tend to break.
- Better inlet maintenance is recommended.
- Inlets cannot be placed at any desired location.
 - Inlets should be placed correctly to avoid compromising the structures supporting the deck and wheel loads.
 - It is recommended to place inlets outside the wheel path when possible.

Clogging of Pipes

- It is recommended to provide enough cleanouts, especially at the end of pipe runs.

- Using T-connections instead of 90° bends is recommended.
 - The last T-connection contains a blind flange. Drain cleaning can be done by running a snake down the blind flange.
 - Cleaning at the bent is done vertically with a snake.
- It is recommended to provide enough expansion joints with fixed points. Downspouts could break if expansion joints are not provided with fixed points.

Diameter of Pipes

- Pipes should be sized based on runoff requirements. Pipes do not perform well if not sized correctly.
- The pipe diameters should be determined based on hydraulic design.

Slope of Pipes

- Pipe slope is limited by the bridge grade.
- Increasing pipe slope could result in pipes ending up below the beams.
 - Pipes below the beams control the bridge's clearance and may pose a danger to trucks.
 - Raising the bridge up to provide sufficient clearance is expensive.
- On flat sections, it is recommended to start downspouts shallow at the inlet and slope them down to the bent whenever possible.

Design of Bridge Deck Drains

Type of Closed Systems

- Closed deck drains are usually used on complex structures with complex geometry (e.g., interchanges, bridges with underlying roadways).
- Increasing ponding width, when possible, can decrease the need for bridge deck drains. Ponding requirements depend on the size and use of the structure.
- Ponding is only be limited to the shoulder when a bridge is made up of one lane and one shoulder for each direction.
- It may be possible to drain water to one or both ends of a bridge if a railway exists below. Draining at the end of a bridge is possible if the railway's right of way can be avoided there.

Hung Systems

- Hung systems are preferred to embedded systems by the structural and hydraulics design teams.
 - Hung systems are simpler to install.
 - Hung pipes are easier to maintain than embedded pipes.
- Failure of embedded PVC pipes is perhaps tolerable.
 - A concrete void acts as a concrete pipe.
 - Columns are designed with the extra area already to handle axial loads.
 - Embedded pipes are not exposed to Ultraviolet (UV) light. Therefore, they could last longer.
- Running water down the pipe helps cool the pipe down during large concrete pours.
- Although embedded systems are complicated to design, they are not designed at the early stages of the project. Early design is recommended when using embedded systems.
- Embedded systems are more durable but more complicated to design.
- Steel pipes could be designed to be part of columns' reinforcing matrices.
 - Using steel pipes as reinforcement is observed in dam and mass concrete industries.
- Embedded systems are aesthetically superior to hung systems.
- It is recommended to paint hung pipes to match the bridge's color. Painting pipes improves aesthetics.

Spacing of Drains

- Existing design methods are sufficient if followed closely.
- Bridge deck drains do not get the attention they need in terms of maintenance.

Construction of Bridge Deck Drains

Construction

- Construction debris can get in drains.
- Sand in pipes is difficult to wash away.
- It is recommended for designers to set and document requirements for pipe hangers and pipe hangers spacings instead of leaving them up to the contractors.

- It is recommended for designers to specify expansion joints' fixed points. Expansion joints will not work correctly if they do not have fixed points.
 - If no fixed points are provided for expansion joints, the expansion will go to the weakest joint that could cause a downspout break.
- It is recommended to have better inspections during construction.
 - Some inspectors are rarely on the job site because they deal with 4 or 5 different projects simultaneously. On their limited time on the job site, they may not give adequate attention to the drains.
- It is recommended not to leave too many decisions for contractors.
- Providing more detailed plans is recommended.

Maintenance and Inspection of Bridge Deck Drains

Maintenance Frequency

- Deck drains should be maintained after sanding operations for bad weather.
 - Bridge deck drains need to be cleaned out after removing sand from the deck.
 - Sweepers push sand into deck drains.
- If salt is used, make sure it is removed to prevent corrosion caused by salty water.
- Maintenance of deck drains is recommended to be done at least once a year.
- Inspection for drains that clog frequently is recommended to be done twice a year.
 - Maintaining bridge deck drains twice a year could be less problematic than maintaining them once a year.
- It is recommended to maintain grates properly.
 - Grates prevent debris from going in the drains (e.g., pieces of paper, cans).
 - At least 50% of the drain's flow capacity is lost if a can is wedged at the first elbow!
- Maintenance before the rainy season is recommended.

Recommended Cleaning Tools

- Cleanouts on bridge deck drain downspouts help conduct maintenance of the bridge.
 - Eliminate the need to stop bridge traffic or close a lane.
- Providing enough cleanouts is recommended to decrease the distance between cleanouts and make maintenance easier.

- High-pressure water is not recommended when there are multiple inlets in one system.
 - Water will shoot out of other drains instead of unplugging the plugged drain.
- A combination of a vacuum system with a pressure washer is recommended to remove clogging.
- Loose washing with a vacuum system will help remove debris and dirt.
- Use rooters to remove objects from drains.
- Short radius elbows are not recommended.
- Long radius elbows are recommended.
 - Do not clog as easily as short radius elbows.
 - Require more space than short radius elbows.
- Use T-connections when possible.
- Expansion joints need to be installed properly.
 - One side of the expansion joint needs to be fixed to the structure or the bent cap.
 - The movement will go to the weakest expansion joint if expansion joints are not fixed on one side. The absence of fixed points on one side for expansion joints could break downspouts.

Assets and Inventory Data

- The information collected on bridge deck drains depends on the inspector's notes.
- Having an asset management system for bridge deck drains as a part of the existing bridge asset management is recommended. Bridge deck drains' element level of inspection would assure a detailed and thorough inspection of bridge deck drains.

General Comments

- It is recommended for designers to design bridge deck drain at early project stages.
- A comprehensive design that considers the following is needed:
 - Maximum spacing of pipe supports.
 - Locations of expansion joints.
 - Locations of expansion joints' fixed points.
 - Amount of movement expansion joints should accommodate.

- Bridge deck drains are not well-integrated systems. Their designs are done late, and many decisions are left to contractors instead of the design team.
- Contractors could make the mistake of installing drains backward or at the wrong locations.

4.4.4 Interview Number 4 (Beaumont, TxDOT)

Failure of Bridge Deck Drains

Common Problems

- Clogging of inlets is the most common problem with bridge deck drains.
- Routine maintenance (cleaning) is essential for bridge deck drains.
- Ensuring the occurrence of routine maintenance can be an issue.

Clogging of Pipes

- Screens can be used to prevent clogging. Screens are typically used at wastewater treatment plants. Frequent maintenance is required for screens.

Diameter of Pipes

- It is recommended to use 8" pipes as a minimum. Larger pipes may be needed in wetter parts of the state.

Slope of Pipes

- Increasing pipe slope is desirable but not feasible.

Design of Bridge Deck Drains

Type of Closed Systems

- Open systems are always preferred but certainly not the most appropriate where the right of way is tight.

Hung Systems

- Pilasters may be used around pipes extended down columns to make them more aesthetically pleasing.
- It is recommended to use hung systems instead of embedded systems. Embedded systems are problematic to maintain if issues arise.

Spacing of Drains

- Drain spacing should be designed based on rainfall events for a specific region. Additional requirements will not be needed if bridge deck drains were designed accordingly.

Construction of Bridge Deck Drains

Construction

- Ensure inspectors are on the job site when bridge deck drains are being installed and enforce the specifications.

Maintenance and Inspection of Bridge Deck Drains

Maintenance Frequency

- It is recommended to conduct maintenance after major rain events (5" or higher) or biannually. Regions without rain (e.g., Odessa) may require less maintenance.

Recommended Cleaning Tools

- Roto-rooters may damage bridge deck drains but is it unlikely.

Assets and Inventory Data

- TxDOT does not collect information on bridge deck drains. All information on bridge deck drains is acquired from as-builts.
- Tracking inspections through asset management is done on bridges. Adding separate asset management for bridge deck drains would require more maintenance forces.

General Comments

- Design and install drains conscientiously.
- Slotted drains could work fine in limited applications.
- Too often, blanket policies are implemented or followed that don't vet all the considerations that may go into a design or scenario.

4.4.5 Interview Number 5 (Lufkin, TxDOT)

Failure of Bridge Deck Drains

Common Problems

- Clogging of inlets is an issue in the Lufkin District.
 - Lufkin has a lot of industrial and agricultural activities. Debris often finds its way to inlets during storm events. The debris will accumulate in drains and render the systems useless.
- It is recommended to design larger openings for steel grates to allow the passage of medium to small debris in hung systems, if possible.
 - Larger openings may be dangerous for cyclists, especially for dual-purpose shoulders (draining and cycling).
 - The outlet's location (e.g., over a waterway) and the area the bridge is located in (e.g., contaminated debris) will control whether to allow debris in drains or not.
 - Bridge shoulders in Lufkin are used for draining purposes only.
- It is recommended to use the correct type of material to help remove stormwater from bridges.
 - Ultraviolet (UV) light will cause PolyVinyl Chloride (PVC) pipes to degrade and fracture.
 - It is recommended to use a UV-resistant pipe material.
- It is recommended to use larger pipe diameters than 8".
- It is recommended to include cleanouts where debris typically accumulates (e.g., at bends).

Clogging of Pipes

- Clogging will not be an issue if there is sufficient water volume and water velocity in the pipes.
 - It is recommended for the runoff in pipes to reach self-cleansing velocities.

Diameter of Pipes

- It is recommended to use pipes larger than 8" in diameter. Larger diameter pipes will convey more water off the bridge deck.

Slope of Pipes

- It is recommended to design the pipes with slopes high enough to achieve self-cleansing velocities.

Design of Bridge Deck Drains

Type of Closed System

- Runoff is carried away when roadways exist below a bridge. Runoff is carried to a location where no roadways will be located below the bridge.
- Runoff can free-fall on rivers or streams unless there are contamination concerns.
 - It is recommended to convey the runoff to an outfall located on the soil at places where contamination is an issue. The runoff may need cleaning to some extent before reaching the body of water.

Hung System Aesthetics

- Embedded systems will not have issues as long as they are cleaned regularly and will not have issues regarding infiltration in the future.
 - Water always finds a way to the steel. Bridge degradation will occur in this case.
 - It is recommended for bridge deck drains to be integrated and sealed properly.
- Hung systems are not aesthetically pleasing, but they are easier to install and maintain than embedded systems.
- Hung systems are selected because:
 - Hung systems cost less than embedded systems.
 - Hung systems function better than embedded systems.
 - Hung systems are easier to maintain.
 - Aesthetics are typically overlooked because of the above reasons.

Spacing of Bridge Deck Drains

- It is recommended to design bridge deck drains based on rainfall events of each zone separately.
- It is recommended to have inlets designed with adequate sizing to handle peak events.
 - Adequate inlet sizes can minimize the hydroplaning of vehicles.
- For a previous project, plans were submitted to the bridge division for review. Since Lufkin is an area that experiences a lot of precipitation, the plans were sent back to the job site containing many unexpected additional inlets.

Construction of Bridge Deck Drains

Construction of Bridge Deck Drains

- After bridge construction, a thorough inspection is done according to a punch list by TxDOT.
 - On large projects, inspecting everything can be tricky.
 - It is hard to find out the issues that cannot be visually observed in closed systems.
- It is recommended for inspectors to make sure that contractors clean after construction to avoid future maintenance issues.
- Drains must be placed exactly according to the plans during construction, especially on large projects.
 - The plans will be sent to the consultant or design team if the error of omissions occurs.

Maintenance & Inspection of Bridge Deck Drains

Frequency of Maintenance

- Bridge Inspection is done every 2 years.
- It is recommended to sweep decks every 2 weeks.
 - If the bridge deck stays relatively clean, bridge deck drains will stay relatively clean too.
 - It is recommended to prioritize sweeping for bridges that have closed systems.

Recommended Cleaning Tools

- When grass grows out of scuppers, it is recommended to:
 - Remove the inlet.
 - Use a shovel to remove the grass.
 - Use water or high-pressure air to remove any buildups in the system.

Assets & Inventory Data

- Consultants were paid to collect elemental data for existing inventories 2 years ago.
 - Some districts might have more information on bridge deck drains if they requested the information 2 years ago.
- Bridge inspection records have bridge deck drains as a sub-item to be given a rating. Consultants or inspectors can leave comments on the sub-item if needed.
 - Drains that perform poorly can be identified and addressed.
- TxDOT has a partnership with Texas Natural Resources Information System (TNRIS). TNRIS provides spatial information to TxDOT.
 - TNRIS provides historical and current geospatial data. The data include natural resources, census, emergency management, and socioeconomic data.
- It is recommended to have GIS references of all bridge deck drains (open and closed systems) and their outlets.
 - GIS references will help to create maintenance plans for bridge deck drains.

General Recommendations

- It is recommended to use pipes larger than 8" in diameter.
- It is recommended to use larger openings for inlets and bridge decks.
 - Larger openings and larger pipe diameters will ensure the system never fully clogs.
- It is recommended to embed pipes only if:
 - Embedded drains would be made from suitable materials.
 - Sufficient amount of cleanouts would be provided.

4.4.6 Interview Number 6 (NCDOT)

Failure of Bridge Deck Drains

Common Problems

- Clogging of bridge deck drains is the most common problem with bridge deck drains.
- The design includes a 50% clogging assumption.

Clogging of Pipes

- Pipes break at joints.
- Clogging of drains is a matter of maintenance.
- NCDOT recommends using 8" diameter pipes.

Diameter of Pipes

- Increasing the pipe size may be a potential solution for clogging.
- Increasing the pipe size may delay clogging instead of preventing it.

Slope of Pipes

- Increasing pipe slope helps prevent clogging.
- Increasing pipe slope is not always feasible.
- Increasing pipe slope will result in pipes controlling the vertical clearance.

Design of Bridge Deck Drains

Type of Closed System

- Environmental regulations are the main reason for using closed bridge deck drains in North Carolina.
- Closed systems are also used when roadways or railways are located below a bridge.
- NCDOT avoids using closed bridge deck drains when possible.
- NCDOT determines whether to use closed systems or not on a case-by-case basis (e.g., unique water resource or waterway where direct discharge would not be allowed).

- NCDOT justifies the use of direct discharge on waterways through two previous studies:
 - It was proven through the first study that the majority of stormwater on bridges have low levels of contaminants.
 - The second study was done recently by the United States Geological Survey (USGS). The project is called Stochastic Empirical Loading and Dilution Model (SELDM). SELDM allows agencies to quantify the possible impacts of receiving waters. The USGS partnered with NCDOT to develop a North Carolina enhanced variation of SELDM that includes North Carolina data about streamflow and water quality. NCDOT uses SELDM to justify the use of open systems on bridge deck drains. The data added will help decision makers assess and mitigate the potential effects of highway runoff on receiving waters in North Carolina. NCDOT plans on releasing the enhanced model for free public use when it is complete. SELDM allows users to (1) Simulate storm flows, concentrations, and loads. (2) Calculate the risk of exceeding water-quality criteria with and without user-defined BMPs. (3) Calculate annual runoff loads. (4) Do a simple annual lake-loading analysis.

Hung System Aesthetics

- Most closed bridge deck drains used in North Carolina are hung on the exterior drains. Only a few cases of embedded drains exist in North Carolina.

Construction of Bridge Deck Drains

Construction of Bridge Deck Drains

- Inspectors must ensure that no construction materials are left in drains.
- NCDOT's standards and specifications for bridge construction keep the jobsite relatively clean.
- Whenever contractors make mistakes or change designs, the resident office would contact the department to assess the changes as quickly as possible.

Maintenance & Inspection of Bridge Deck Drains

Frequency of Maintenance

- Bridge inspection is done every 2 years.
- Usually, no issues are found when drains are inspected.
- Issues with drains are addressed immediately when found.

- Issues with drains are noted during inspections and sent to the maintenance team. Maintenance would then depend on available personnel and funding.
 - Acquiring funds for bridge deck drain maintenance could be difficult because higher prioritized systems might need maintenance.
- A risk-based approach inspection is recommended. A risk-based approach will require some bridges to have shorter inspection cycles (e.g., bridges that deal with large amounts of debris).
- Maintenance only depends on the inspector's notes. No regular preventative maintenance is scheduled for bridge deck drains in North Carolina.

Assets & Inventory Data

- NCDOT is moving towards using spatial information for its asset management systems.
- It is recommended to have an asset management system to keep track of locations and conditions of bridge deck drains.
- Since bridge deck drains have aspects that relate to stormwater management strategies, they might require their own asset management system.
- It is recommended to have an asset management system as a part of the existing bridge asset management system.

General Recommendations

- NCDOT tries to avoid using closed deck drains as much as possible.
- Adding more drains on a bridge might create more issues instead of solving them.
- NCDOT recommends using open gutters or troughs instead of closed bridge deck drains.

CHAPTER 5 - SUMMARY AND RECOMMENDATIONS OF BEST PRACTICES

5.1 Summary

The data collected from the literature review, survey questionnaire, and follow-up interviews were analyzed in this chapter. Through extensive literature review, a detailed understanding was obtained about bridge deck drains' failures, designs, construction, and maintenance and inspection in Texas and other states. By conducting two surveys (one for TxDOT districts and another for other states), responses were collected from 17 TxDOT districts and 21 states other than Texas. Responses were also collected from DC and Quebec, Canada. The responses from Texas were collected from the TxDOT districts of Abilene, Amarillo, Atlanta, Austin, Beaumont, Bryan, Dallas, El Paso, Fort Worth, Houston, Lufkin, Odessa, Paris, Pharr, San Angelo, San Antonio, and Tyler. The out-of-state responses were collected from Colorado, Florida, Georgia, Iowa, Kansas, Louisiana, Maine, Michigan, Nebraska, New Hampshire, New Jersey, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Carolina, Virginia, and Washington. After evaluating the survey responses, recommendations for bridge deck drains were identified. The surveys were followed by interviews with respondents from NCDOT and five TxDOT districts: Austin, Beaumont, Dallas, Houston, and Lufkin. These interviews aimed to identify the interviewees' best practices and recommendations for bridge deck drains.

5.2 Recommendation of Best Practices

After evaluation of bridge deck drain failures, designs, construction, and maintenance, the most effective practices were identified and presented here:

- Most survey respondents and interviewees recommended hung systems when compared to embedded systems. Hung systems are easier to design, install, maintain, and repair. Rupture is easier to detect on hung systems. Installation of hung systems is done after bridge construction. If embedded systems cannot be avoided, it is recommended to start

designing embedded systems early during bridge design because their design decisions are interdependent.

- It is recommended to preserve the aesthetics of hung systems to prevent drivers from getting distracted. This can be achieved through the following recommendations:
 - Minimize the number of fittings (bends and elbows).
 - Conceal pipes between beams.
 - Place drains on the invisible side of columns.
 - Paint the pipes to match the color of the structure they are mounted on.
 - Slope the pipes similar to the slopes of the profile grades of the bridges.

Figure 5.1 Shows different aesthetic examples for hung systems.



Figure 5.1 Hung system Aesthetics: (a) Aesthetically Displeasing System (b) Aesthetically Pleasing System (Yildiz Dak, 2010; NJDOT, 2011)

- It is recommended to allow runoff free-fall through openings in barriers or curbs on bridges when permissible (no facilities or waterways below). If the roadway below is made up of only a few lanes, restrict free-fall from above the roadway and allow free-fall again after

passing the roadway. It is also essential to check that there are no environmental concerns or risks of contamination from the runoff. Figure 5.2 shows an example of barrier openings discontinuing over a roadway.



Figure 5.2 Free-fall Discontinues Over a Roadway in Houston

- It is recommended to use curb openings instead of bridge deck drains unless deck drains cannot be avoided (e.g., contaminants in runoff requiring closed systems over waterways). Curb openings allow free-fall of runoff, making them an open system. Curb openings are cheaper than drains and would not require the same level of maintenance. Openings can also substitute the use of bridge deck drains in some cases. An example of curb openings on a bridge is shown in Figure 5.3.



Figure 5.3 Bridge Curb Opening: (a) Steel Bridge Rail (b) Concrete Curb (C) Bridge Slab (TxDOT, 2021)

- It is recommended to have a minimum profile grade of 0.5% and a transverse slope of 2% for bridge decks to carry the runoff away effectively. It is recommended to provide inlet drains at appropriate spacings based on the frequency of the design runoff event and the spread of water. Adequate spacing results in effective runoff interception by bridge deck drains.
- It is recommended to select grate inlet designs based on each bridge characteristics. Since each bridge location receives different amounts of precipitation and debris, and not all bridges accommodate cyclists, different designs of grate inlets may be used for different bridges. Various grate inlets differ in hydraulic efficiency, debris handling efficiency, and bicycle safety. It is recommended to use longer inlets for bridge decks with steep gutter slopes. Longer inlets help prevent splash-over and allow for effective capturing of runoff. It is recommended to have the bars of grate inlets parallel to traffic when there are no bicycle safety concerns. Parallel bars are the most hydraulically efficient among grate inlets. Bars perpendicular to traffic can be made more efficient with vanes.

- It is recommended to minimize the number of bends in closed bridge deck drains. It is recommended to use long radius elbows instead of short radius elbows. Long radius elbows clog less but require more space. Since most of the debris accumulates at bends, it is recommended to provide cleanout plugs at bends. It is crucial to make sure that enough cleanouts are considered in the design of bridge deck drains. Cleanout plugs also allow maintenance to be done off bridges so that traffic control on bridges would not be needed. It is recommended to use T-connections instead of 90° bends since T-connections offer an extra side to be used as a cleanout. Figure 5.4 shows cleanout plugs for hung systems.



Figure 5.4 Hung and Embedded Systems Cleanout Plugs in Houston

- If a bridge has a low point, it is recommended to provide an inlet at the low point and two additional flanking inlets, one on each side, as shown in Figure 5.5. Flanking inlets relieve the inlet at the low point if the design storm is exceeded or the inlet is clogged.

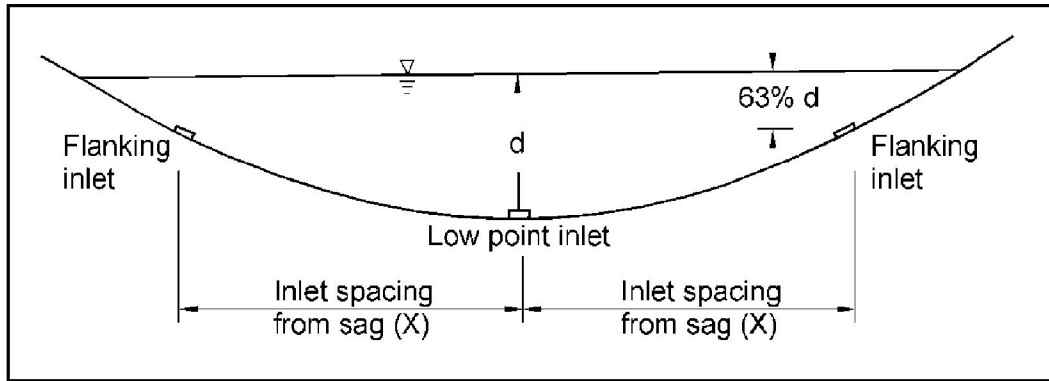


Figure 5.5 Flanking Inlets Placed Near Low Point (FHWA, 2013)

- It is recommended to have the drains away from the curbs (Figure 5.6). Having the drains away from the curbs allow for a gradual transition from the weir to orifice flow (Hammonds et al., 1995). The capacity of drains placed away from curbs is less than the capacities of the drains placed near the curbs. Therefore, it is recommended to use deeper, larger drain pans and larger outlet pipes to compensate for the decrease in capacity (Hammonds et al., 1995).

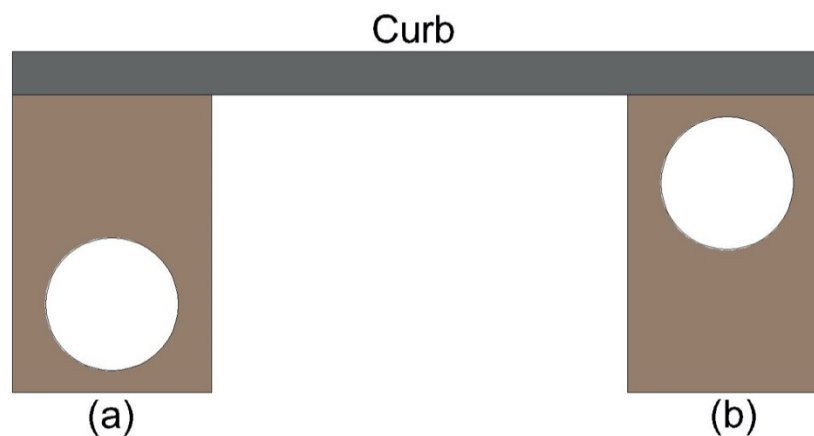


Figure 5.6 Different Drain Orientations: (a) Drain Close to Curb (b) Drain Away from Curb
(Adapted from Hammonds et al., 1995)

- It is recommended to make sure the designers include a fixed point for each expansion joint. If fixed points are not provided for expansion joints, the expansion will go to the weakest joint. When the expansion goes to the weakest joint, downspouts could break since the deck moves, and the bent is rigid.
- It is recommended to design pipes to achieve self-cleansing velocities. It is recommended to use pipes larger than 8” on bridges where debris is a critical issue. It is recommended to have enough space for pipes to be sloped adequately without allowing pipes to control the vertical clearance. An example of pipes sloped along the deck is shown in Figure 5.7.



Figure 5.7 Pipes Sloped Along Bridge Profile Grade (Hennegan, 2021)

- It is recommended to standardize the design and detailing of closed bridge deck drains. Detailed design of closed systems is recommended for all bridges (regardless of their sizes) that require closed systems. Detailed drawings eliminate difficulties that contractors and inspectors face on the job site.
- It is recommended to provide a splash block for free-falls that are less than 25 feet to prevent surface erosion. Free-falls over 25 feet disperse the water enough so that no surface erosion occurs.

- It is recommended to ensure that contractors place drains precisely where they are designed to be located on all bridges. It is recommended to have the details of bridge deck drains set by designers instead of leaving any decisions to contractors. It is recommended to ensure inspectors are present during the installation of bridge deck drains.
- It is recommended to inspect bridge deck drains at least once before each rainy season, especially for those with high amounts of debris. The bridge deck drains should be maintained if any issues are identified during inspections.
- It is recommended to conduct regular inspections for closed bridge deck drains. Inspection of pipes near bends is highly recommended. It is recommended to fully document the performance and condition of each drain on bridges. It may be possible to document inlet conditions by walking on the shoulder along the bridge (does not necessarily require traffic control).
- A recommended approach to remove clogging in drains is to use a vacuum system with a pressure washer. Loose washing with a vacuum system can remove debris and dirt. Roto-rooters can be used to remove objects from drains. Caution must be used when using roto-rooters to avoid damaging drains. Figure 5.8 shows these cleaning tools.

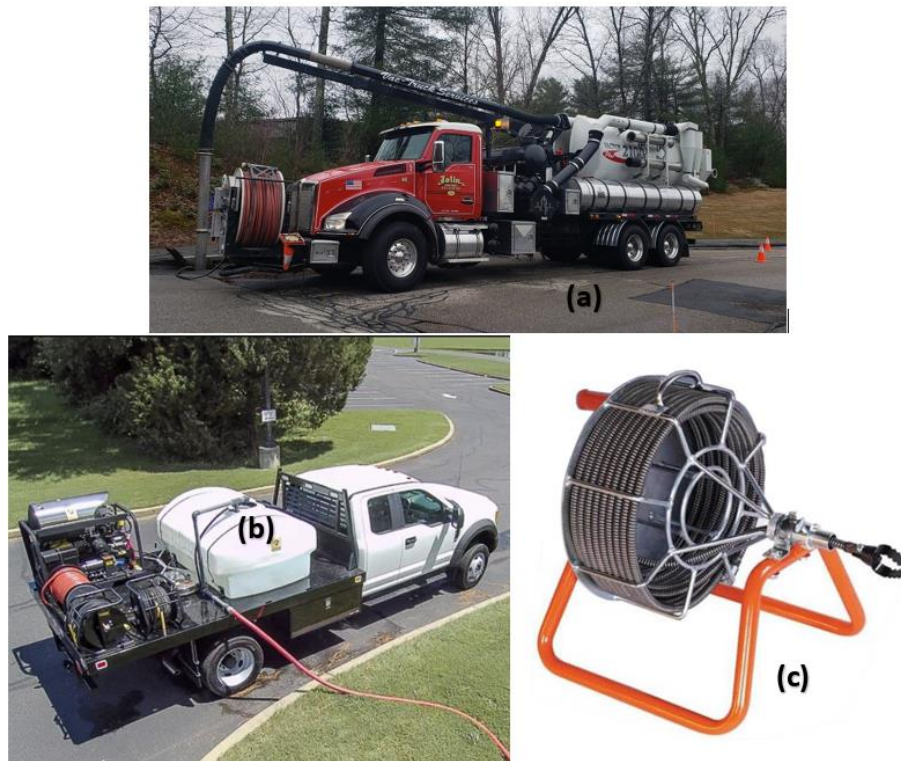


Figure 5.8 Recommended Cleaning Tools: (a) Vacuum Truck (b) Truck-Mounted Pressure Washer (c) Roto-Rooter (Jolin, 2021; Cougar Chemical, 2021; Rent-All, 2021)

- It is recommended to monitor and evaluate drains on young bridges. Corrective actions should be taken if any issues are found. It is recommended to pour water down the drains or wait for precipitation to observe the performance of bridge deck drains.
- It is recommended to manage bridge deck drains through the bridge asset management system. It is recommended that the TxDOT bridge asset management system's drains section be re-evaluated to ensure that adequate information about the conditions and performances of deck drains is collected to keep them perform well. Bridges are inspected once every two years. This inspection frequency does not seem to be adequate for bridge deck drains.

- It is recommended for TxDOT to invest in the, soon to be released, enhanced Stochastic Empirical Dilution Model (SELDM) by NCDOT. SELDM was initially developed by the USGS. NCDOT improved the model and added North Carolina data to it. The data added will help decision makers assess and mitigate the potential effects of highway runoff on receiving waters in North Carolina. SELDM will help TxDOT quantify the contaminants a bridge receives in the runoff. After quantifying the contaminants, it may be permissible to use open systems instead of closed systems.

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APPENDIX A – TEXAS SURVEY QUESTIONNAIRE



Project Description

The University of Texas at Arlington invites you to participate in a short survey pertaining to the state of practice in design and maintenance of bridge deck drains. This survey is an integral part of the TxDOT Research and Technology Implementation (RTI) Project #0-7092, titled: “Synthesis: Bridge Deck Drains.” This survey aims to capture the state of practice in design and maintenance of bridge deck drains performed by TxDOT maintenance staff. We expect this survey to take approximately 10 minutes. TxDOT and our research team highly appreciate your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research. If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

A-1 CONTACT INFORMATION:

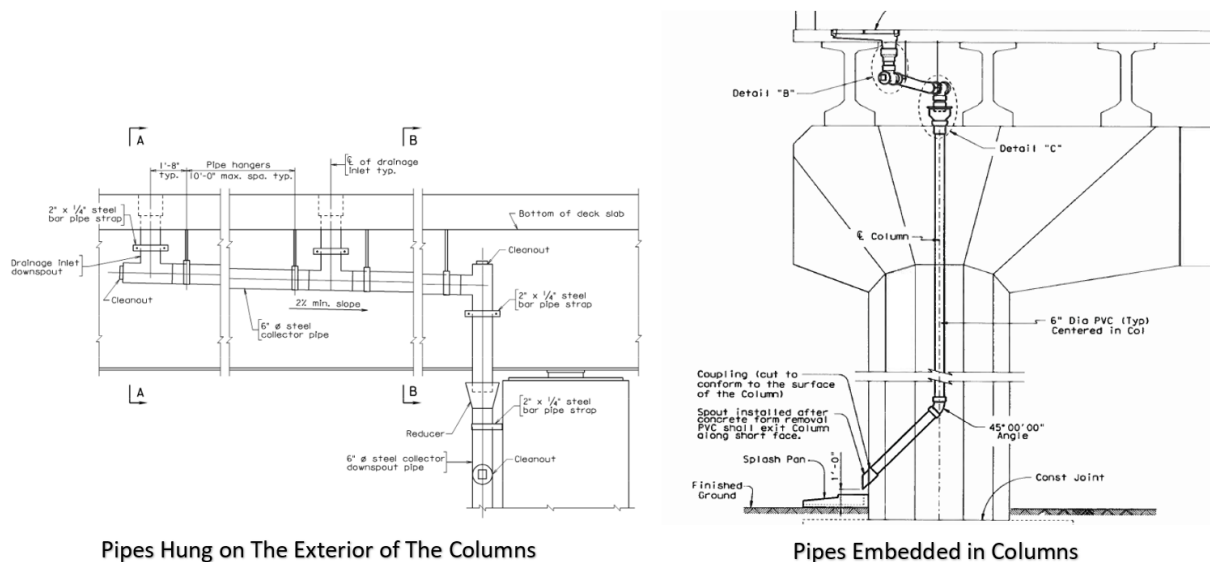
- Name:
 - Position:
 - District:
 - City/Town:
 - E-mail:
-

A-2 BRIDGE DECK DRAIN FAILURE

Bridge Deck Drains

Bridge Deck Drain systems can either be open or closed systems.

Closed systems consist of grate inlets and pipes. Closed systems can either be hung on the exterior of the columns or embedded in the concrete columns.



1. How often does flooding occur on your bridges? (Select only one.)

- During rare severe rainfalls
- Once a year
- More than once a year
- During each rainfall

2. How long is the duration of typical floods on bridges due to drain failures? (Select only one.)

- Less than 30 minutes
- 30 minutes – 1 hour
- 1 – 2 hours
- More than 2 hours

3. Please select the common problems that occur with bridge deck drains in your district. (Check all that apply.)
- Corrosion of inlets
 - Corrosion of pipes
 - Inlet breaking due to traffic load
 - Clogging of inlets
 - Inlet popping out of placement
 - Insufficient inlet capacity
 - Pipes clogging due to bends
 - Pipes clogging due to T-connections
 - Pipes clogging due to insufficient pipe diameter
 - Deflection of pipes
 - Cyclist or pedestrian injuries due to inlet design
 - Poor bridge deck drain spacing
 - Grates broken or missing
 - Improper cross slope creates ponds
 - Cracking of pipes
 - Other _____
-

A-3 BRIDGE DECK DRAIN DESIGN

4. What are the reasons for selecting closed bridge deck drains? (Check all that apply.)
- Environmental regulations
 - Span of bridge
 - Type of road (e.g., highway, rural)
 - Level of service
 - Existing facilities or waterways underneath the bridge
 - Type of bridge (e.g., truss, arch, beam)
 - Expected service life of closed deck drains
 - Durability
 - Future construction on or underneath the bridge
 - Longitudinal slope
 - Roadway geometry
 - Transverse slope
 - Other _____

-
5. What are the reasons for selecting hung on the exterior of the columns closed systems? (Check all that apply.)
- Freeze and thaw damage resulted from embedded systems
 - Roadway geometry
 - Locations and spacing of inlets
 - Locations of outlets
 - Locations of cleanout plugs
 - Other _____
6. What are the reasons for using embedded closed systems? (Check all that apply.)
- Aesthetics
 - Roadway geometry
 - Locations and spacing of inlets
 - Locations of outlets
 - Locations of cleanout plugs
 - Scour prevention
 - Corrosion prevention
 - Other _____
7. Based on experience, which type of closed system do you prefer? (Select only one.)
- Hung on the exterior of the columns
 - Embedded in columns
8. What is your top priority for design improvements in bridge deck drain designs? (Select only one.)
- Design of grate inlets
 - Design of scupper inlets
 - Design of inlet box (e.g., slope, area, depth)
 - Change of pipe material
 - Increase in pipe size
 - Location of deck drains
 - Spacing of deck drains
 - Slope of pipes
 - Increase of inlet length
 - Increase of inlet width
 - Other _____

9. Do you have any recommendations for improving bridge deck drain designs? If yes, please explain

A-4 BRIDGE DECK DRAIN CONSTRUCTION

10. Are there any construction practices that you have found to affect the service life or performance of bridge deck drains negatively? If yes, please explain.

11. Do you have any recommendations for improving bridge deck drain construction and installation? If yes, please explain.

A-5 BRIDGE DECK DRAIN MAINTENANCE AND INSPECTION

12. Who maintains bridge deck drains after installation? (Check all that apply.)

- Your agency
- Outsourced to a private contractor
- Another government agency
- Other _____

13. Where is the runoff typically drained to? (Select only one.)
- Junction box then transported to a storm sewer system
 - Soil below the bridge
 - Open channel
 - Waterways below the bridge
 - Other _____
14. What types of inspections take place on bridge deck drains in your district? (Check all that apply.)
- Initial (inventory)
 - Routine (periodic)
 - Damage
 - In-depth
 - Special (interim; inspection scheduled at the discretion of the bridge owner) (e.g., monitor clogging)
 - Yearly
15. What inventory data does your agency have to help manage bridge deck drains? (Check all that apply.)
- Number of bridge deck drains
 - Locations of bridge deck drains
 - GPS coordinates of bridge deck drains
 - Existing conditions of bridge deck drains
 - Performance of bridge deck drains
 - Photographs
 - Videos
 - Age of bridge deck drains
 - Number of cleanout plugs
 - Expected service life of bridge deck drains
 - Inspection dates
 - Material of pipes
 - Sizes of pipes
 - Material of inlets
 - Types of inlets
 - Size of inlets
 - Areas of inlet openings
 - No inventory exists
 - Other _____

16. What descriptions characterize your approach to preserving/maintaining bridge deck drains? (Check all that apply.)

- Regular preventive maintenance
- Immediate repairs after damage or failure
- Corrective repairs prioritized and scheduled to meet a performance target
- Repair the worst drain first
- Little or no preventative maintenance work performed annually
- This agency does not maintain bridge deck drains

17. Method and schedule of maintenance in your agency depends on: (Check all that apply.)

- Inspection recommendations
- Age of bridge deck drains
- Expected costs
- Customer complaints
- Observed performance and rating
- Agency's guidelines (e.g., programs, spreadsheets, work sheets)
- Other _____

18. How do you determine where a deck drain is in its service life? (Check all that apply.)

- Compare age with expected service life
- Deterioration models
- Visual inspection
- Photo-logging
- Video-logging
- Operational performance
- Assets are repaired or replaced as soon as they fail without regard to service life
- Service life is often determined more by functional obsolescence than by wear-and-tear
- Customer complaints
- The agency does not monitor service life for this type of asset
- Other _____

19. Do you have any recommendations for improving the service life of deck drains? (Check all that apply.)

- Conducting regular preventative maintenance
- Placing drains conscientiously
- Increasing number of cleanout plugs
- Increasing slope of pipes
- Including vanes for grate inlet designs
- Changing pipe material
- Decreasing length of downspout pipes
- Other _____

20. What equipment or machinery are used to clean and maintain bridge deck drains in your district? (Check all that apply.)

- Hand or hand tools (e.g., snakes)
 - Compressed air
 - Flushing with water using low-pressure, high-volume water
 - Flushing with water using high-pressure, low-volume water
 - High-pressure power washer
 - Vacuum trucks
 - Water jets
 - Water truck with power washer
 - Shovels
 - Maintenance and cleaning outsourced to a private contractor
 - Other _____
-

A-6 FURTHER INFORMATION

21. Our follow-up interview is designed to acquire practical information about the state of practice on bridge deck drains. Are you willing to share your insight in a follow-up interview?

- Yes
- No

APPENDIX B – OUT OF STATE SURVEY QUESTIONNAIRE



Project Description

The University of Texas at Arlington invites you to participate in a short survey pertaining to the state of practice in design and maintenance of bridge deck drains. This survey is an integral part of the TxDOT Research and Technology Implementation (RTI) Project #0-7092, titled: “Synthesis: Bridge Deck Drains.” This survey aims to capture the state of practice in design and maintenance of bridge deck drains performed by State DOTs maintenance staff. We expect this survey to take approximately 10 minutes. TxDOT and our research team highly appreciate your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research. If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

B-1 CONTACT INFORMATION:

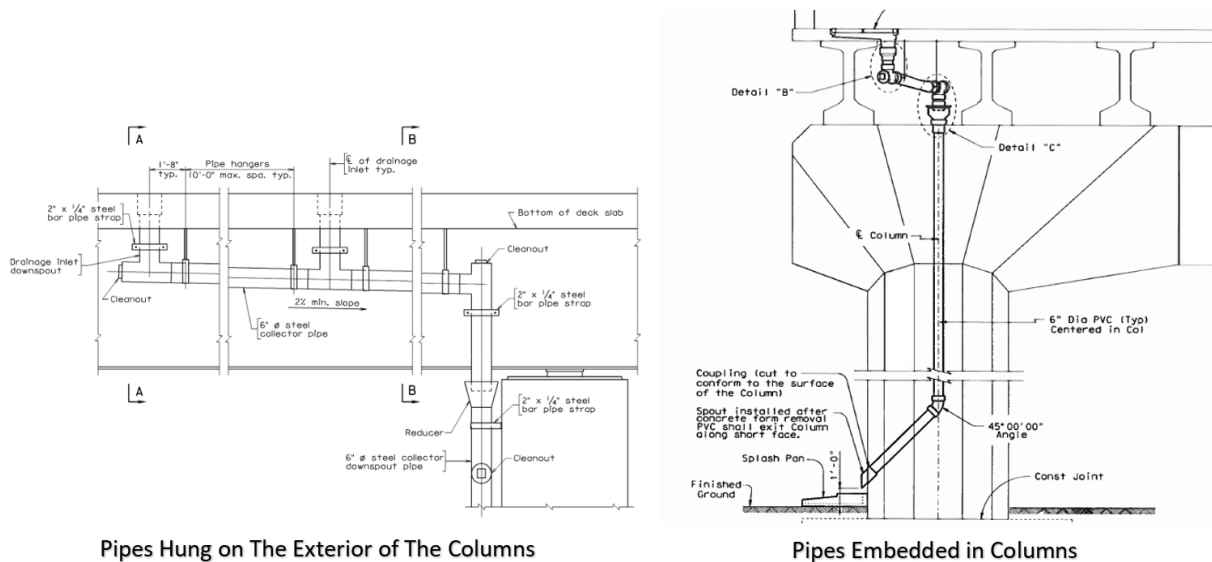
- Name:
 - Agency:
 - City/Town:
 - State:
 - E-mail:
-

B-2 BRIDGE DECK DRAIN FAILURE

Bridge Deck Drains

Bridge Deck Drain systems can either be open or closed systems.

Closed systems consist of grate inlets and pipes. Closed systems can either be hung on the exterior of the columns or embedded in the concrete columns.



1. How often does flooding occur on your bridges? (Select only one.)
 - During rare severe rainfalls
 - Once a year
 - More than once a year
 - During each rainfall

2. How long is the duration of typical floods on bridges due to drain failures? (Select only one.)
 - Less than 30 minutes
 - 30 minutes - 1 hour
 - 1 - 2 hours
 - More than 2 hours

3. Please select the common problems that occur with bridge deck drains in your state. (Check all that apply.)
- Corrosion of inlets
 - Corrosion of pipes
 - Inlet breaking due to traffic load
 - Clogging of inlets
 - Inlet popping out of placement
 - Insufficient inlet capacity
 - Pipes clogging due to bends
 - Pipes clogging due to T-connections
 - Pipes clogging due to insufficient pipe diameter
 - Deflection of pipes
 - Cyclist or pedestrian injuries due to inlet design
 - Poor bridge deck drain spacing
 - Grates broken or missing
 - Improper cross slope creates ponds
 - Cracking of pipes
 - Other _____
-

B-3 BRIDGE DECK DRAIN DESIGN

4. What are the reasons for selecting closed bridge deck drains? (Check all that apply.)
- Environmental regulations
 - Span of bridge
 - Type of road (e.g., highway, rural)
 - Level of service
 - Existing facilities or waterways underneath the bridge
 - Type of bridge (e.g., truss, arch, beam)
 - Expected service life of closed deck drains
 - Durability
 - Future construction on or underneath the bridge
 - Longitudinal slope
 - Roadway geometry
 - Transverse slope
 - Other _____

-
5. What are the reasons for selecting hung on the exterior of the columns closed systems? (Check all that apply.)
- Freeze and thaw damage resulted from embedded systems
 - Roadway geometry
 - Locations and spacing of inlets
 - Locations of outlets
 - Locations of cleanout plugs
 - Other _____
6. What are the reasons for using embedded closed systems? (Check all that apply.)
- Aesthetics
 - Roadway geometry
 - Locations and spacing of inlets
 - Locations of outlets
 - Locations of cleanout plugs
 - Scour prevention
 - Corrosion prevention
 - Other _____
7. Based on experience, which type of closed system do you prefer? (Select only one.)
- Hung on the exterior of the columns
 - Embedded in columns
8. What pipe material does your agency often use for closed bridge deck drains? (Select only one.)
- Polyvinyl Chloride
 - Steel
 - Fiberglass
 - Ductile Iron
 - Other _____

9. What are the reasons for using that material type? (Check all that apply.)

- Flexibility
- Lightweight
- Ease of installation
- Durability
- Resistance to chemical attacks
- Resistance to corrosion
- Smooth inner walls
- Low price
- High availability
- Low maintenance requirements
- Ultraviolet light resistance

Other _____

10. What are the common problems that you found with this pipe material?

11. What is your top priority for design improvements in bridge deck drain designs? (Select only one.)

- Design of grate inlets
- Design of scupper inlets
- Design of inlet box (e.g., slope, area, depth)
- Change of pipe material
- Increase in pipe size
- Location of deck drains
- Spacing of deck drains
- Slope of pipes
- Increase of inlet length
- Increase of inlet width
- Other _____

12. Do you have any recommendations for improving bridge deck drain designs? If yes, please explain

13. Are you aware of any innovative methods or systems in design that your DOT or other state DOTs have used? If yes, please explain.

B-4 BRIDGE DECK DRAIN CONSTRUCTION

14. Are there any construction practices that you have found to affect the service life or performance of bridge deck drains negatively? If yes, please explain.

15. Do you have any recommendations for improving bridge deck drain construction and installation? If yes, please explain.

B-5 BRIDGE DECK DRAIN MAINTENANCE AND INSPECTION

16. Who maintains bridge deck drains after installation? (Check all that apply.)

- Your agency
- Outsourced to a private contractor
- Another government agency
- Other _____

17. Where is the runoff typically drained to? (Select only one.)

- Junction box then transported to a storm sewer system
- Soil below the bridge
- Open channel
- Waterways below the bridge
- Other _____

18. What types of inspections take place on bridge deck drains in your state? (Check all that apply.)

- Initial (inventory)
- Routine (periodic)
- Damage
- In-depth
- Special (interim; inspection scheduled at the discretion of the bridge owner) (e.g., monitor clogging)
- Yearly

19. What inventory data does your agency have to help manage bridge deck drains? (Check all that apply.)

- Number of bridge deck drains
- Locations of bridge deck drains
- GPS coordinates of bridge deck drains
- Existing conditions of bridge deck drains
- Performance of bridge deck drains
- Photographs
- Videos
- Age of bridge deck drains
- Number of cleanout plugs
- Expected service life of bridge deck drains
- Inspection dates
- Material of pipes
- Sizes of pipes
- Material of inlets
- Types of inlets
- Size of inlets
- Areas of inlet openings
- No inventory exists
- Other _____

20. What descriptions characterize your approach to preserving/maintaining bridge deck drains? (Check all that apply.)

- Regular preventive maintenance
- Immediate repairs after damage or failure
- Corrective repairs prioritized and scheduled to meet a performance target
- Repair the worst drain first
- Little or no preventative maintenance work performed annually
- This agency does not maintain bridge deck drains

21. Method and schedule of maintenance in your agency depends on: (Check all that apply.)

- Inspection recommendations
- Age of bridge deck drains
- Expected costs
- Customer complaints
- Observed performance and rating
- Agency's guidelines (e.g., programs, spreadsheets, work sheets)
- Other _____

22. How do you determine when a deck drain is in its service life? (Check all that apply)
- Compare age with expected service life
 - Deterioration models
 - Visual inspection
 - Photo-logging
 - Video-logging
 - Operational performance
 - Assets are repaired or replaced as soon as they fail without regard to service life
 - Service life is often determined more by functional obsolescence than by wear-and-tear
 - Customer complaints
 - The agency does not monitor service life for this type of asset
 - Other _____
23. Do you have any recommendations for improving the service life of deck drains? (Check all that apply.)
- Conducting regular preventative maintenance
 - Placing drains conscientiously
 - Increasing number of cleanout plugs
 - Increasing slope of pipes
 - Including vanes for grate inlet designs
 - Changing pipe material
 - Decreasing length of downspout pipes
 - Other _____
24. What equipment or machinery are used to clean and maintain bridge deck drains in your state? (Check all that apply.)
- Hand or hand tools (e.g., snakes)
 - Compressed air
 - Flushing with water using low-pressure, high-volume water
 - Flushing with water using high-pressure, low-volume water
 - High-pressure power washer
 - Vacuum trucks
 - Water jets
 - Water truck with power washer
 - Shovels
 - Maintenance and cleaning outsourced to a private contractor
 - Other _____
-

B-6 FURTHER INFORMATION

25. Our follow-up interview is designed to acquire practical information about the state of practice on bridge deck drains. Are you willing to share your insight in a follow-up interview?

- Yes
- No

APPENDIX C – SURVEY INVITATION EMAIL FOR TEXAS DISTRICTS

To:

Subject: Synthesis of Bridge Deck Drains.

My name is Mohsen Shahandashti, and I am asking you to participate in a UT Arlington research study titled, “Synthesis: Bridge Deck Drains.” This survey is an integral part of the TxDOT Research and Technology Implementation (RTI) Project #0-7092. This survey aims to capture the state of practice in design and maintenance of bridge deck drains performed by TxDOT maintenance staff. You can choose to participate in this research study if you are at least 18 years old.

Reasons why you might want to participate in this study include helping research team identify best practices in the design and maintenance of bridge deck drains, but you might not want to participate if you are not able to commit to taking a survey that is expected to take 10 minutes. Your decision about whether to participate is entirely up to you. If you decide not to be in the study, there won't be any punishment or penalty; whatever your choice, there will be no impact on any benefits or services that you would normally receive. Even if you choose to begin the study, you can also change your mind and quit at any time without any consequences.

If you decide to participate in this research study, I will ask you to complete for the research are to answer 22 questions. It should take about 10 minutes. Although you probably won't experience any personal benefits from participating, the study activities are not expected to pose any additional risks beyond those that you would normally experience in your regular everyday life or during routine medical / psychological visits. You will not be paid for completing this study.

The research team is committed to protecting your rights and privacy as a research subject. We may publish or present the results, but your name will not be used. While absolute confidentiality cannot be guaranteed, the research team will make every effort to protect the confidentiality of your records as described here and to the extent permitted by law. If you have questions about the study, you can contact me at 817-272-3723 or mohsen@uta.edu. For questions about your rights or to report complaints, contact the UTA Research Office at 817-272-3723 or regulatoryservices@uta.edu.

APPENDIX D – SURVEY INVITATION EMAIL FOR STATE DOT OTHER THAN TXDOT

To:

Subject: Synthesis of Bridge Deck Drains.

My name is Mohsen Shahandashti, and I am asking you to participate in a UT Arlington research study titled, “Synthesis: Bridge Deck Drains.” This survey is an integral part of the TxDOT Research and Technology Implementation (RTI) Project #0-7092. This survey aims to capture the state of practice in design and maintenance of bridge deck drains performed by TxDOT maintenance staff. You can choose to participate in this research study if you are at least 18 years old.

Reasons why you might want to participate in this study include helping research team identify best practices in the design and maintenance of bridge deck drains, but you might not want to participate if you are not able to commit to taking a survey that is expected to take 10 minutes. Your decision about whether to participate is entirely up to you. If you decide not to be in the study, there won't be any punishment or penalty; whatever your choice, there will be no impact on any benefits or services that you would normally receive. Even if you choose to begin the study, you can also change your mind and quit at any time without any consequences.

If you decide to participate in this research study, I will ask you to complete for the research are to answer 25 questions. It should take about 10 minutes. Although you probably won't experience any personal benefits from participating, the study activities are not expected to pose any additional risks beyond those that you would normally experience in your regular everyday life or during routine medical / psychological visits. You will not be paid for completing this study.

The research team is committed to protecting your rights and privacy as a research subject. We may publish or present the results, but your name will not be used. While absolute confidentiality cannot be guaranteed, the research team will make every effort to protect the confidentiality of your records as described here and to the extent permitted by law. If you have questions about the study, you can contact me at 817-272-3723 or mohsen@uta.edu. For questions about your rights or to report complaints, contact the UTA Research Office at 817-272-3723 or regulatoryservices@uta.edu.

APPENDIX E – VALUE OF SYNTHESIS OF BRIDGE DECK DRAINS

INTRODUCTION

Table E-1 presents the summary of the value of research (VoR) estimation for Project 0-7092 based on several functional areas. In this table, the benefit areas are associated with qualitative and economic (quantitative) benefits. Qualitative benefits of transportation research are those benefits that may not be directly quantifiable, such as safety (Ashuri et al., 2014). On the other hand, the quantitative benefits are those that can be quantified as savings after implementation, such as reduction in construction operations and maintenance costs (Shahandashti et al., 2017).

Table E - 1 The Project's Value of Research (VoR)

<i>Benefit Area</i>	<i>Qual</i>	<i>Econ</i>	<i>Both</i>	<i>TxDOT</i>	<i>State</i>	<i>Both</i>
Reduced Operations and Maintenance Costs		x		x		
Level of Knowledge	x			x		
Safety	x					x
System Reliability	x			x		
Reduced Administrative Costs	x			x		
Customer Satisfaction	x					x

Notes: Qual: Qualitative; Econ: Economic; TxDOT: Texas Department of Transportation; State: State of Texas.

REDUCED OPERATIONS AND MAINTENANCE COSTS

Water must be drained from bridge decks to protect drivers, cyclists, and pedestrians from hydroplaning vehicles. A drainage system that prevents the accumulation of substantial water depths will reduce the risk of hydroplaning (INGOV, 2012). Hydroplaning is also one of the main causes of lawsuits against state DOTs (Smith, T., 2016). As a recent example, many vehicles hydroplaned and crashed on different days on a bridge on I-74 in Illinois back in March 2021 (Ickes, B., 2021). Upon investigation, it was found that one scupper inlet was clogged. The clogged inlet caused massive water build-up that in turn caused vehicles to hydroplane and crash (KWQC, 2021).

Over 85% of weather-related crashes in Texas are caused by rain (TDI, 2020). Using the query builder on TxDOT's Crash Records Information System's website (CRIS), data on crashes occurring due to rain on bridges were obtained. The data is summarized in Table E-2.

Table E - 2 Statistics on crashes due to rain on Texas bridges

Bridge Detail (How the Crashes Involved Bridges)	Number of Crashes (Direct & Indirect Crashes) Due to Rain on Texas Bridges				
	2016	2017	2018	2019	2020
Structure Not Hit	90	91	85	85	72
Vehicle Retained on Bridge or Overpass	221	242	323	245	249
Vehicle Went Between Parallel Structures	5	8	5	4	3
Vehicle Went Over Rail	3	12	8	7	7
Vehicle Went Through Rail	7	14	11	10	7
Total Crashes	326	367	432	351	338

Note: Bridge detail: Whether and how a bridge was directly or indirectly involved in a crash (TxDOT, 2021).

In 2020, crashes count reached 474,549 in Texas (TxDOT, 2021). As shown in Table E-2, there were 338 crashes due to rain on Texas bridges in 2020 alone. Assuming TxDOT can only achieve 10% reduction of accidents by reducing hydroplaning events, at least 33 crashes on bridge due to rain can be avoided each year. By evaluating TxDOT's distribution of crash types (Table E-3) with FHWA recommended comprehensive crash costs (Harmon and Gross, 2018), an approximate amount of saving could be calculated. It was calculated that by preventing 33 crashes caused by rain on Texas bridges, TxDOT could save approximately \$6.45 Million dollars in 2020. (Table E-4).


Table E - 3 Distribution of types of crashes for 474,549 accidents in 2020

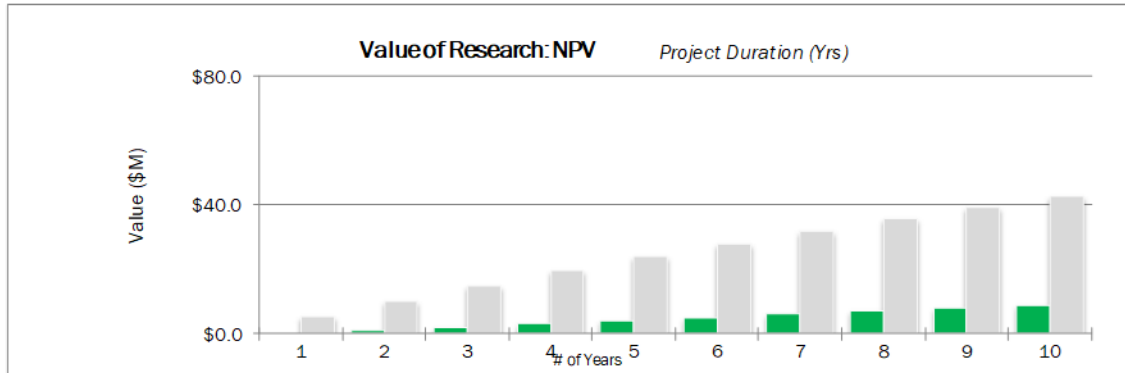
	Fatalities	Suspected Serious Injuries	Non-incapacitating Crashes	Possible Injuries	Non-Injury
TxDOT distribution of type of crashes in 2020	0.82%	3.09%	13.17%	27.04%	189%

Table E - 4 Projected annual savings in Texas by reducing accidents that occur due to rain by 10%

	Fatalities	Suspected Serious Injuries	Non-incapacitating Injuries	Possible Injuries	Non-injuries
KABCO Comprehensive Crash Unit Cost 2016	\$11,295,400	\$655,000	\$198,500	\$125,600	\$11,900
TxDOT \$ Saving per Category	\$3,056,535	\$667,904	\$862,701	\$1,120,754	\$742,203
Total TxDOT Saving per Year	\$6,450,097				

The comprehensive crash costs used in our calculations include tangible impact (economic costs) along with costs associated with physical pain, discomfort, anxiety, and emotional distress resulted from accidents (Harmon et al., 2018). In a 10-year horizon, assuming that the discount rate is 5% and 10% of accidents can be avoided by reducing hydroplaning, the net present value of improving bridge deck drains will be over \$46 million (Figure E-1).

	Project # 0-7092	
	Project Name: Synthesis of Bridge Deck Drains	
	Agency: UTA	Project Budget \$ 49,999
	Project Duration (Yrs) 1.0	Exp. Value (per Yr) \$ 5,545,329
Expected Value Duration (Yrs) 10		Discount Rate 5%
Economic Value		
Total Savings: \$ 55,403,291		Net Present Value (NPV): \$ 46,014,182
Payback Period (Yrs): 0.009016		Cost Benefit Ratio (CBR, \$1 : \$__): \$ 920



Years	Expected Value	Years	Expected Value	Expected Value	Expected Value	NPV
0	\$5,495,330	0	\$5,495,330	\$5,495,330	\$5.50	\$5.23
1	\$5,545,329	1	\$5,545,329	\$11,040,659	\$11.04	\$10.26
2	\$5,545,329	2	\$5,545,329	\$16,585,988	\$16.59	\$15.05
3	\$5,545,329	3	\$5,545,329	\$22,131,317	\$22.13	\$19.62
4	\$5,545,329	4	\$5,545,329	\$27,676,646	\$27.68	\$23.96
5	\$5,545,329	5	\$5,545,329	\$33,221,975	\$33.22	\$28.10
6	\$5,545,329	6	\$5,545,329	\$38,767,304	\$38.77	\$32.04
7	\$5,545,329	7	\$5,545,329	\$44,312,633	\$44.31	\$35.79
8	\$5,545,329	8	\$5,545,329	\$49,857,962	\$49.86	\$39.37
9	\$5,545,329	9	\$5,545,329	\$55,403,291	\$55.40	\$42.77
10	\$5,545,329	10	\$5,545,329	\$60,948,620	\$60.95	\$46.01

Notes:

Amounts on Value of Research are estimates.
Project cost should be expensed at a rate of no more than the expected value per year.
This electronic form contains formulas that may be corrupted when adding or deleting rows, by variables within the spreadsheet, or by conversion of the spreadsheet. The university is responsible for the accuracy of the Value of Research submitted.

Figure E - 1 Value of synthesis of bridge deck drains

SAFETY

The runoff from the bridge deck should be drained to reduce the risk of hydroplaning of vehicles. If enough water depth is accumulated to separate tires from the bridge deck, tires lose traction, increasing the chance of hydroplaning (Young et al., 1993). More than 10% of crashes in Texas are due to poor weather conditions (TDI, 2020). Assuming hydroplaning can be reduced by 10%, it is expected that this research is going to prevent 33 crashes in Texas annually. Details of the types of crashes and injuries (by considering TxDOT distribution of crash and injury types) have been presented in Table E-5.

Table E - 5 Distribution of crash and injury types for prevented crashes

	Fatal Crashes	Fatalities	Suspected serious crashes	Suspected Serious Injuries	Non-incapacitating Crashes	Non-incapacitating Injuries	Possible Injury Crashes	Possible Injuries	Non-injury Crashes	Non-injuries
Distribution of crash and injury types for the 33 prevented crashes	0.24	0.27	0.84	1.02	3.2	4.36	5.75	8.91	21.43	62.04

LEVEL OF KNOWLEDGE

The information on bridge deck drains is extensive but not concentrated. First and foremost, this research collected the latest information on bridge deck drains from many TxDOT districts and other states in the USA. By synthesizing all the gathered information, this research recommended design, construction, and maintenance practices for bridge deck drains.

SYSTEM RELIABILITY

Preventing crashes (discussed in Section "Reduced Operations and Maintenance Costs") results in fewer lane closures and decreased travel time. So, implementing this research could have a significant impact on system reliability. This research project adds value by providing recommendations for improving bridge deck drain design, construction, and maintenance.

REDUCED ADMINISTRATIVE COSTS

Clearing accidents on roads and controlling subsequent damages (paying for lawsuits or insurance) require administrative paperwork. Reducing collisions due to hydroplaning results in a decrease in the costs associated with administrative tasks. This research provides value with respect to this benefit area by offering recommendations for bridge deck drain design, construction, and maintenance.

CUSTOMER SATISFACTION

By improving the safety of bridges when it rains, the number of accidents on roadways could be decreased. Reducing the number of accidents is a direct contributor to customer satisfaction. Having a safe and smooth traffic flow when it rains will reduce delays caused by accidents and decrease customer dissatisfaction resulting from road closure.