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Evaluation of Traffic Safety Improvements at Low Water Crossings

Research Report 0-6992-R1

Cooperative Research Program

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COLLEGE STATION, TEXAS

TEXAS DEPARTMENT OF TRANSPORTATION

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16. Abstract

Texas leads the nation in flood-related deaths. The majority of deaths are caused by motorists attempting to drive through moving water. Motorists attempt to cross a flooded roadway because they do not realize its depth, especially at nighttime during heavy storms that make it difficult to see the flooded road. The National Weather Service reports that it only takes 18–24 inches of moving water to sweep away a truck, and 6 inches to float a small car. While it may be impractical to raise or remove all low water crossings (LWCs) across the state, there are low-cost means to better alert the driving public to the risks of LWCs.

Texas A&M Transportation Institute researchers investigated low-cost approaches to improve LWCs, with a focus on easy-to-install and -maintain features, such as:

- Reflective pavement markings and markers.
- Flood detection sensors.
- Active/passive warning devices.
- Infrastructure-to-infrastructure and infrastructure-to-vehicle technologies.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Chiara Silvestri Dobrovolny, Ph.D. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lb/in^2

*SI is the symbol for the International System of Units

LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Definition
AC	Acrylic Cylinder
ADT	Average Daily Traffic
ALERT	Automated Local Evaluation in Real Time
BSM	Basic Safety Message
C2C	Center to Center
COTS	Commercial Off-the-Shelf
CRIS	Crash Records Information System
CV	Connected Vehicle
C-V2X	Cellular Vehicle to Everything
DMS	Dynamic Message Sign
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communication
FAS	Flood Alert System
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
FRWS	Flooded Road Warning System
FW DSS	Flood-Warning Decision-Support System
GUI	Graphical User Interface
HCRS	Highway Condition Reporting System
I2I	Infrastructure to Infrastructure
I2V	Infrastructure to Vehicle
IIRPM	Internally Illuminated Raised Pavement Marker
IPCC	Intergovernmental Panel on Climate Change
ITS	Intelligent Transportation System
KDT	Knowledge Discovery in Text
LED	Light-Emitting Diode
LWC	Low Water Crossing
NCHRP	National Cooperative Highway Research Program
NLP	Natural Language Processing
NTU	Nephelometric Turbidity Units
NWS	National Weather Service
OBU	Onboard Unit
RHiNO	Roadway Highway Inventory Network Offload
RL	Retroreflected Luminance
RRPM	Raised Retroreflective Pavement Marker
RSM	Roadside Safety Message
RSU	Roadside Unit
SOS	Surface Observation System
SRD	Sediment Retention Device
TAPCO	Traffic & Parking Control Company
TMC	Traffic Management Center

TNRIS	Texas Natural Resources Information System
TPB	Theory of Planned Behavior
TTI	Texas A&M Transportation Institute
TxMUTCD	*Texas Manual on Uniform Traffic Control Devices*
VAR	Vent Area Ratio
WMO	World Meteorological Organization
WT	Water Tank

Chapter 1. INTRODUCTION

1.1 BACKGROUND

Texas leads the nation in flood-related deaths. Most of these deaths occur when motorists drive through moving water. Motorists attempt to cross a flooded roadway because they often do not realize how deep the water is in the crossing. This problem is particularly acute at nighttime during heavy storms when it is difficult to see that water is over the roadway. The National Weather Service reports that it takes only 18–24 inches of moving water to sweep away a truck and 6 inches of moving water to sweep a high-profile vehicle and a small car off the roadway (*1*). Because it is impractical to raise or remove all low water crossings (LWCs) across the state, low-cost means exist to better alert the driving public to the risks of LWCs.

1.2 RESEARCH OBJECTIVES

Texas A&M Transportation Institute (TTI) researchers investigated low-cost approaches to improve LWCs, with a focus on easy-to-install and -maintain features, such as:

- Reflective pavement markings and markers.
- Flood detection sensors.
- Active/passive warning devices.
- Infrastructure-to-infrastructure (I2I) and infrastructure-to-vehicle (I2V) technologies.

The specific objectives of this project were as follows:

- Examine the current state-of-the-practice strategies and technologies used by the Texas Department of Transportation (TxDOT) and other state departments of transportation (DOTs) to monitor and disseminate information to motorists about the status of LWCs during flooding events.
- Examine delineation strategies for improving motorists' understanding of water depths and the status of flooded LWCs.
- Assess the current state of flood detection sensors and their potential applications to LWCs in Texas.
- Develop and conduct a proof-of-concept demonstration of an I2V application for disseminating information to motorists about LWCs.
- Recommend and test low-cost delineation strategies for four LWCs on Texas roadways.

1.3 RESEARCH APPROACH AND ORGANIZATION OF REPORT

Figure 1-1 shows the approach followed by the researchers to achieve the research objectives. The researchers first developed a synthesis of relevant information by reviewing the research literature and state policy documents regarding LWC safety improvements (Task 2). Chapter 2 of this report provides a summary of the findings of this literature review.

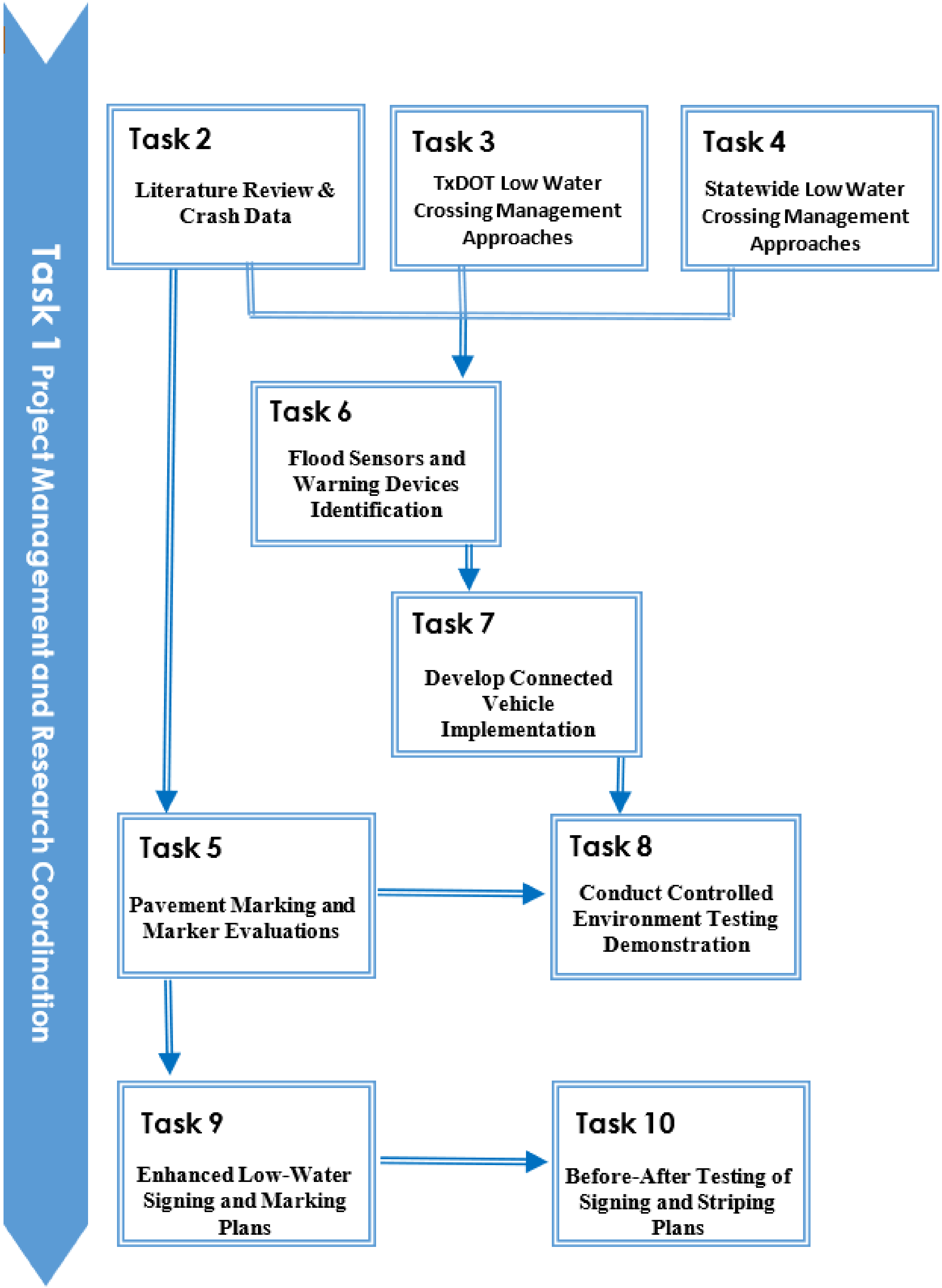


Figure 1-1. Approach Followed to Achieve Research Objectives.

Following the detailed literature review, the researchers then conducted an online survey of TxDOT (Task 3) and other state DOTs (Task 4) on strategies and techniques for delineating and disseminating information about LWCs. The researchers designed the survey with the additional intent to identify and categorize types of both passive and active devices utilized by the surveyed agencies to improve conspicuity and alert motorists of flooding events at LWCs. Chapter 3 of this report summarizes the results of these surveys.

The researchers investigated each TxDOT area office's current inventory and management approach for LWCs (Task 3). Using the Texas Natural Resources Information System (TNRIS), a database containing the location of LWCs in Texas, the researchers located all existing LWC locations. The researchers then used this list to identify LWCs in association with traffic crashes during flood events. A database on the LWCs in association with traffic crashes was created (P3). The researchers reviewed the most recent available five years from the Crash Records Information System (CRIS) database to identify the extent of the LWC traffic incidents and other available information regarding those locations. Chapter 4 summarizes the results of this activity.

The researchers also evaluated marking and marker contrast, comparing when the road surface is submerged and not submerged in water during both day and night conditions (Task 5). The evaluation included assessing whether the change in visual contrast between submerged and unsubmerged markings provides drivers with enough detection distance to stop safely. Chapter 5 summarizes the procedures and findings associated with this evaluation.

The researchers conducted a review of existing sensors and devices currently on the market, including existing countermeasures, for flood sensors and high-water warning devices currently being used by TxDOT, along with other off-the-shelf flood sensors and warning devices available. The researchers also conducted laboratory testing to assess the capabilities and robustness of up to three flood sensors and a combination of sensors identified in Task 6. Chapter 6 summarizes the review of sensor technology, while Chapter 7 provides the findings of the assessment of flood detection technologies.

In addition, the researchers designed a prototype system for providing alerts and warnings at LWCs using connected vehicle (CV) technology (Task 7). The system used appropriate I2I and I2V technologies for providing flood condition reports at LWCs in a CV environment. The researchers considered two different architectures: one integrated with TxDOT's LoneStar Traffic Management System software, and another designed as a standalone system for deployment at an isolated LWC. The researchers then conducted proof-of-concept testing of the prototype system at the Texas A&M University RELLIS Campus (Task 8). Chapter 8 of this report summarizes the prototype system's design, while Chapter 9 provides the results of the controlled field study testing of the prototype.

The researchers worked with the Bryan and Beaumont Districts to develop and implement innovative signing and marking plans to improve driver situational awareness of LWCs (Task 9). The researchers developed a generic signing and marking plan that can be deployed by TxDOT contract crews. The recommended signs, markings, and raised retroreflective pavement markers (RRPMs) were to be installed at four crossings within two districts. Chapter 10 provides an overview of these recommended strategies.

Initially, the researchers planned to conduct before-and-after comparisons of the sign and marking improvements at the three crossings (Task 10). However, due to travel restrictions and stay-at-home work orders caused by the COVID-19 outbreak, the researchers could not travel to the sites to conduct these detailed field studies of delineation improvements proposed for the LWCs. The researchers will continue to work with TxDOT to conduct field assessments of the proposed delineation strategies at a future date.

Chapter 2. LITERATURE REVIEW AND CRASH DATA ANALYSIS

2.1 INTRODUCTION

An LWC is a structure that provides reasonable access as a stream crossing but floods periodically, closing the roadway to traffic. These structures are relatively inexpensive and particularly suitable for low-volume roads, streams with periodically dry beds, or streams where the typical depth of flow is relatively low (*2*). At most LWCs, traffic is impacted only when water overtops the LWC. These impacts range from a few hours up to multiples days, depending on the location, amount of rainfall, and other factors. Once the water recedes (and local maintenance crews examine the structure to ensure no damage occurred during the hydrologic event), traffic can resume using the LWCs in a usual fashion.

The researchers first conducted a comprehensive search of the literature related to LWC countermeasures and design practices. The researchers used the following scientific citation indexing resources, and citation and abstract databases of the peer-reviewed literature: ScienceDirect, ISI Web of Science, ResearchGate, past TTI publications, state and local agency technical reports, and Transportation Research Information Services Database. The researchers augmented this search with a search on Google Scholar.

The researchers then developed a synthesis of relevant information by reviewing the research literature and state policy documents regarding LWC-related issues. The synthesis consists of a literature review to obtain the best available knowledge on the following topics:

- LWC-related crash and incident trends, focusing on the following variables' effects on crash frequency and severity.
  - Roadway geometry (e.g., lane width, pavement marking, and shoulder type).
  - Traffic control devices (e.g., LWC signs and warning devices).
  - Weather (e.g., precipitation and extreme weather event).
- Effectiveness of different LWC countermeasures (e.g., signs, warning devices).

Bearing in mind the work's objective, the researchers considered only articles related to LWCs and floods. The following sections present a review of the current literature on LWCs and associated topics. The researchers divided the literature review into the following categories:

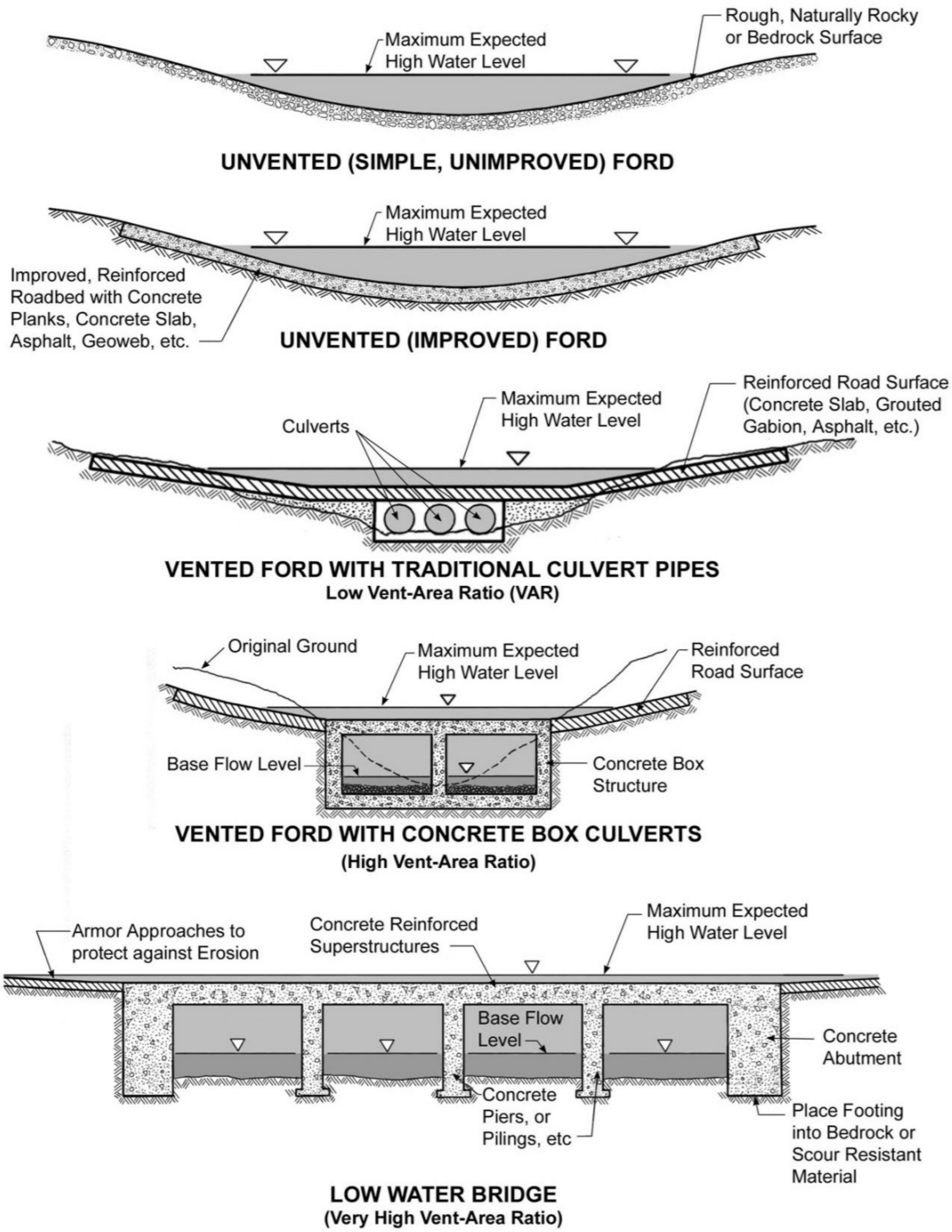
- Design Alternatives and Countermeasures.
- Human Factors.
- Crash and Geometric Characteristics.

2.2 DESIGN ALTERNATIVES AND COUNTERMEASURES

Figure 2-1 shows the three basic types of LWCs:

- Unvented (simple) fords.
- Vented fords.
- Low-water bridges.

Texas highways have all three of these crossings.



Source: (*3*)

Figure 2-1. Types of LWCs.

2.2.1 Unvented Crossings

Figure 2-2 shows a natural low-water unvented ford crossing. Agencies generally use this type of crossing when the streambed is stable and traffic is rare. This design is the least expensive but not necessarily the safest or most environmentally friendly for the stream if the traffic load surpasses the load the crossing is capable of handling. These crossings may cause the stream bed's surface to break down and result in erosion and sediment transport downstream.

Source: (*4*)

Figure 2-2. Unvented Ford Crossing.

Hardening the ford can be a good option. Depending on the soil type, an agency may need to work on the approaches to reduce scouring on the crossing's downstream edge. Narrowing the flow across the ford may not be environmentally friendly because restricting the channel increases the flow velocity. Increased velocity causes increased erosion. Scouring can be very dangerous. The edge cannot be seen in higher flows and could be disastrous if there is a large drop and a vehicle gets off the crossing. Agencies commonly use rip-rap or hard armoring to reduce this effect. Along with scouring on approaches, ruts from traffic and gullies from water running into the stream can form. Proper water diversions are a possible way to lessen this unwanted consequence.

2.2.2 Vented Crossings

With vented crossings, one or more culverts (or vents) elevate the streambed's driving surface. The culverts allow low-flow water to pass beneath the roadbed. The vents can be one or more pipes, box culverts, or open-bottom arches. Vented crossings fall into two categories: low and high vent area ratio (VAR) crossings. Vented crossings with culverts that are small relative to the bankfull channel have a low VAR, while vented crossings that approximate or exceed the bankfull channel's size have a high VAR. Figure 2-3 and Figure 2-4 show examples of these two types of vented crossings.

Source: (*3*)

Figure 2-3. Example of a Low VAR Vented LWC.

Source: (*3*)

Figure 2-4. Example of a High VAR Vented LWC.

2.2.3 Low-Water Bridges

Low-water bridges are generally open-bottom structures with elevated decks. Their spans are generally less than 20 ft, and their design uses one or more piers. Low-water bridges generally have greater capacity and can pass higher flows than most vented and unvented crossings. Low-water bridges are different than regular bridges because the expectation is water will overtop a low-water bridge during a flood event. A low-water bridge must satisfy specific hydrologic, hydraulic, structural, and foundation design requirements. Figure 2-5 shows an example of a low-water bridge.

Source: (*5*)

Figure 2-5. Low-Water Bridge over the Guadalupe River, Gruene, Texas.

2.2.4 Factors

LWCs are not suitable for all roadways. The following subsections outline some of the factors agencies should consider when designing LWCs (*2*, *3*).

2.2.4.1 Travel Speed

LWCs are most practical for roadways that operate with low-to-moderate traffic speeds. Drivers can traverse unimproved fords at speeds less than 10–20 mph. Vented fords with broad, smooth dips and gentle transitions are suitable for travel speeds up to 50 mph. LWCs are not generally ideal for high-speed facilities.

2.2.4.2 Average Daily Traffic (ADT)

Lower-volume roadways are more suitable for LWCs. The consequences and impacts of flooding on traffic flow are less at lower traffic volumes. Exposure is also minimal at lower traffic volumes. Periodic or occasional closures become more impactful as traffic volumes increase.

2.2.4.3 Flow Variability

An LWC may be acceptable in areas with highly variable flows. High, short-duration peaks followed by long intervals of very low or no flow are most conducive to LWCs, as long as drivers can tolerate the interruption.

2.2.4.4 High-Flow Duration

The duration of an overtopping flow controls how long a crossing will be closed. Although weather patterns influence the duration of the flow, watershed attributes also contribute. Characteristics of “flashy” watersheds (where flows rise and fall rapidly) include the following:

- Steep, short drainage bases (high basin relief).
- Small basin area.
- High drainage density (miles stream/basin stream).
- Thin or impermeable soils.
- Little or no flood plain.
- Low vegetation cover.

2.2.4.5 Debris Loading

Agencies should also consider the type and frequency of the debris loading occurring at the crossing. Agencies may want to consider using a low-profile crossing design that allows debris to pass over the road in areas prone to landslides and heavy debris flows. Debris may also impact the structural integrity of the crossing. Sediment deposits on the roadway can also affect pavement friction and durability.

2.2.4.6 Channel Entrenchment

Channel entrenchment refers to the vertical containment of the water flow. Channels deeply incised between the adjacent ground surface and channels closely bounded by steep slopes (confined) generally require a high LWC design.

2.3 COUNTERMEASURES

A countermeasure is a measure or action taken to counter or offset another measure. The agency or designer should develop a facility/structure that can operate and be sustained during extreme situations.

2.3.1 Warning Signs

The *Texas Manual on Uniform Traffic Control Devices* (TxMUTCD) (*6*) provides a standard signing layout for LWCs. The TxMUTCD mandates static warning signs and water depth gauges (as needed) on the approach to an LWC. One study (*7*) suggested an alternative signing strategy that uses one regulatory and two warning signs in advance of an LWC. Signage in every LWC area should start at least 750 ft on both sides in advance of the crossing. The location of the "Flood Area Ahead" sign depends on the maximum approach speed. The "Impassable During High Water" signage should be placed 450 ft in advance, and the "Do Not Enter When Flooded" signage at 200 ft. In specific areas where water can back up more than 750 ft on either side of the structure during a flood event, "Flood Area Ahead" signage should be placed more than 750 ft from the actual crossing, in addition to the signage requirements already mentioned. Furthermore, a "Low Water Crossing" sign can caution people about an LWC ahead. The signage should be placed 500 to 700 ft in advance of the LWC.

Apart from static signage, dynamic/active message signage displaying messages such as "Road Closed Ahead Due to Flooding" or "Caution—Water on Road" may be installed along with blinking beacons, based on the budget of the public agency, type of road, and frequency of flooding at the LWC location.

Many drivers have trouble arbitrating water depth and speed over the roadway in an LWC and enter the flooded road. Lower visibility during nighttime and muddy water during flooding situations pose additional difficulties to drivers making decisions under these conditions. In the absence of credible information, drivers decide on their own if the road is drivable. A wrong decision can lead to a loss of property and life. Flash flood warnings and flood advisories should be distributed to the public via messaging services and radio stations so that the drivers can be attentive to the floodwater conditions.

2.3.2 Barricades and Signs

Barricades and signs are the most widely used countermeasures for LWC scenarios. A study conducted by Coles et al. inspected the usefulness of barricades and signage in discouraging people from driving into flood streams (*8*). The study, which was based on a survey conducted in Tucson, Arizona, found that barricades and signs do not often discourage motorists from entering the flood stream. Barricades and signs can be vague because usually they are not present at all crossings and can remain in position when the location is dry. Ninety percent of responders felt the presence of a barricade or sign designated the probability of a flash flood hazard. Responders who reported they had not driven into the floodwater indicated slightly higher trust levels in barricades and signs than those who had driven into the water stream (*8*).

2.3.3 Structural Modifications

Ashley and Ashley suggested that future structural modifications of flood control designs (e.g., culverts and bridges) may not dramatically reduce the number of fatalities (*9*). Solutions such as installing traffic barricades, alarm signs, and water depth gauges at hazardous locations are not enough. There are many problems associated with these installations. Depth gauges, for example, are not very informative to a layperson. Depth gauges only tell the depth if the driver can figure out how to read it. Color gauges that indicate hazardous water depths may help driver understanding. Barricades, meanwhile, are often installed or uninstalled too late. The driver may see barricades and choose to drive around them or think that their truck or SUV can cross the low-lying water.

2.3.4 Flood Education Program

There is a need to understand how public education can support social norms for appropriate flood behavior since a social norm around not entering floodwater would mean that fewer people may be motivated to enter. The literature highlights trust as an issue. Drivers who trust the signage are more likely to adhere to the message of the signage. Trust of information (and trust in the source of information) is an important aspect in encouraging appropriate behaviors, and consequently should be developed more broadly across flood education programs (*10*).

After a significant flooding event in 2011 in Queensland, Australia, public agency officials devised a two-pronged approach for increasing driver awareness of flood safety. Agencies developed targeted materials for primary school students. They also used public service announcements to increase driver awareness of flooding hotspots. Despite these efforts, Australia continued to experience a significant number of motor-vehicle-related drownings each year (about 7 percent between 2012 and 2013) (*11*, *12*). Researchers suggested that one reason for the continued loss of life was that the program focused on providing information only, rather than understanding the social mental processes that guide common actions in this context.

Additionally, campaigns to persuade behavior change need to have an inherent effect on people’s conduct—in this circumstance, the driver’s choice to drive through a flooded watercourse—to reduce various health-risk performances and decrease such movements more efficiently over time. To efficiently reduce the rate of vehicle-related drownings, it is always necessary to first create empirical evidence on key factors that guide common choice to drive through flooded watercourses (*13*). Innovative analytical models to better understand individual behavior will help in the growth of more effective interference programs to battle this risky driving behavior and ultimately save human lives (*13*, *14*, *15*).

2.4 HUMAN FACTORS

Road traffic crashes are responsible for a substantial fraction of mortality. In this literature review, the researchers attempted to delineate human factors (Figure 2-6) that collectively represent the principal cause of traffic crashes and/or contribute to most of the remaining causes. Some of the key behavioral factors can be distinguished as:

- Reduced capability on a long-term basis (inexperience, aging, disease, disability, alcoholism, drug abuse).
- Reduced capability on a short-term basis (drowsiness, fatigue, acute alcohol intoxication, short-term drug effects, binge eating, acute psychological stress, temporary distraction).
- Risk-taking behavior with long-term impact (overestimation of capabilities, macho attitude, habitual speeding, habitual disregard of traffic regulations, indecent driving behavior, inappropriate sitting while driving, accident proneness).
- Risk-taking behavior with short-term impact (moderate ethanol intake, psychotropic drugs, motor vehicle crime, suicidal behavior, compulsive acts).

This classification assists in the conceptualization of the problem that may also contribute to behavior-modification-based efforts.

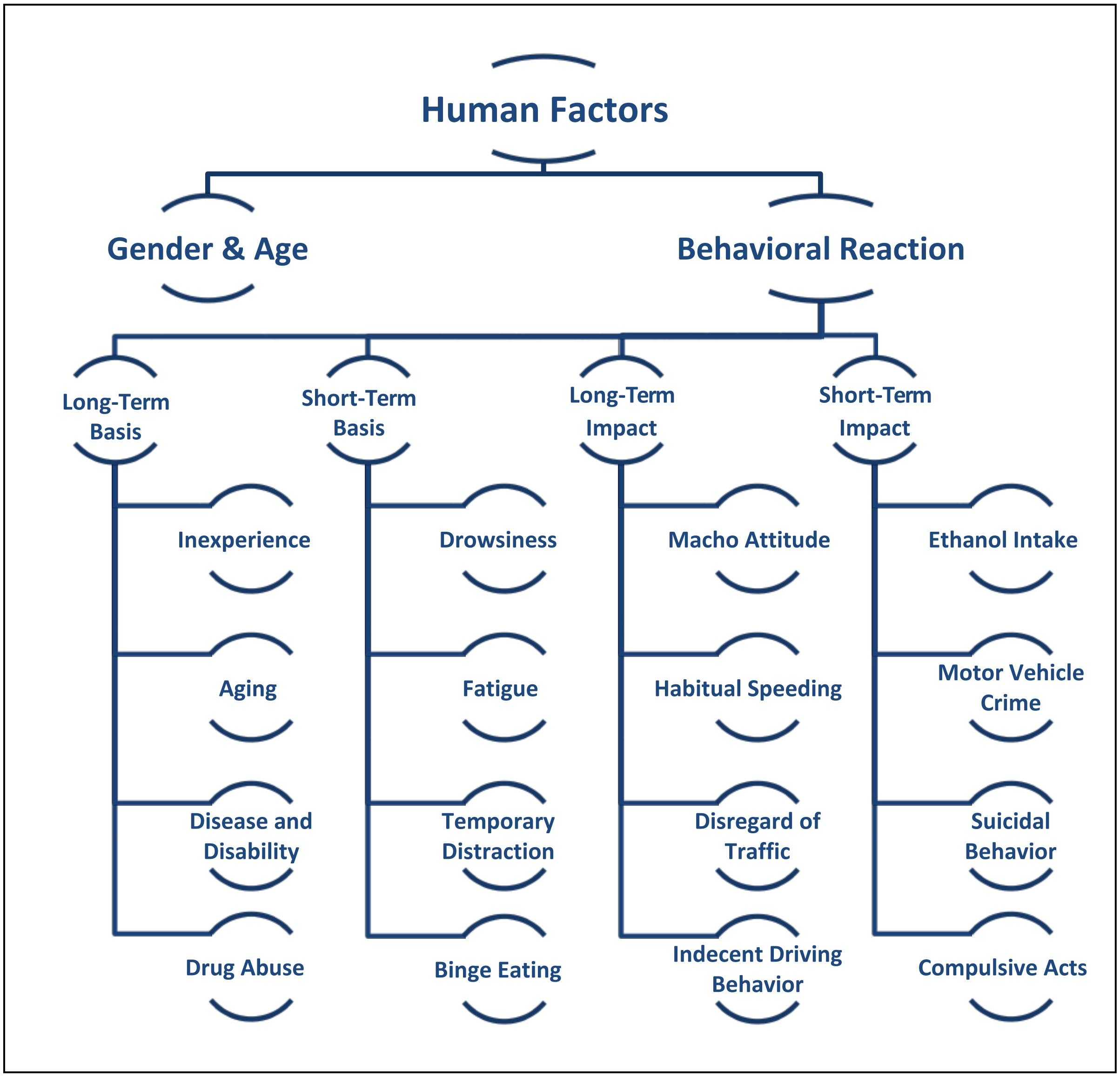


Figure 2-6. Human Factors in Crash Analysis.

2.4.1 Gender and Age

McKenna et al. suggested that the probability of an accident reduces considerably with the presence of a female passenger (*16*). Chen et al. found that the per-capita death rate almost doubled with a male passenger's presence, regardless of who was driving (*17*). Males are overrepresented in vehicle crashes, physical trauma, and pedestrian drownings. Probable contributing factors are the number of males who drive, the high percentage of males who work for supporting and emergency services, and males' risk-taking conduct.

Jonkman and Kelman inspected flood fatalities of U.S. and European flood disasters (1989–2002) and situations surrounding flood-related losses (*18*). They found that the age and gender of flood-associated deaths concluded that the death toll was highest among males. There was an improved susceptibility for those younger than age 21 years and older than 60 years.

Rappaport, who amassed a database of tropical cyclone fatality rates using the National Weather Service (NWS) readings and newspaper reports, also found a higher percentage of male deaths (*19*). While vehicle-related deaths accounted for only 23 percent of the subsequent tropical cyclone fatalities, males accounted for most of those fatalities—although the percentage of male mortalities was less than in several other studies of flood mortalities. Males older than 40 years had 1.5–4.0 times the death proportion of females.

2.4.2 Behavioral Reaction

Flash floods in rural areas are principally challenging for applying mitigating policies because of comparatively large distances to emergency amenities and first responders, lack of extenuating structures in rural areas such as bridges over small watercourses instead of LWCs, less time for people to react to impending disasters, and low visibility at night. Some people may drive onto flooded roads inadvertently, but plenty of evidence suggests that barriers only temporarily stop some traffic from entering. Although a flooded road would seem to present a clear danger, the wish to get to a destination may obfuscate risk perception and evading behavior when facing a flooded roadway (*20*).

The research seems to indicate that most drivers do not fully recognize the dangers associated with flooded roadways. Research examining driving through flooded watercourses revealed several mutual findings:

- Most cars will start to float in as little as 12 inches of water.
- Six inches of water will reach most passenger vehicles' bottommost point, which can cause loss of control (*21*).
- Nearly all vehicles, including four-wheel drives, will float in 24 inches of moving water (*11*).

Once a vehicle begins floating, the water can push it sideways. At this point, most passenger vehicles tend to roll over, leaving only a few seconds for those inside to escape.

The protection of road users is a significant concern in installing an LWC at any site. Fixed warning signs on the approach to an LWC, markers along the edge of toughened surfaces, and water depth gauges are required to protect those using a crossing. Most drivers have trouble determining water speed and depth over the road in an LWC and try to enter the flooded roadway. Lower visibility at night and muddy water in flooding conditions create additional difficulties for drivers making decisions. In the absence of any informative signs, drivers set their own benchmarks to determine whether the road is drivable, leading to property and life loss.

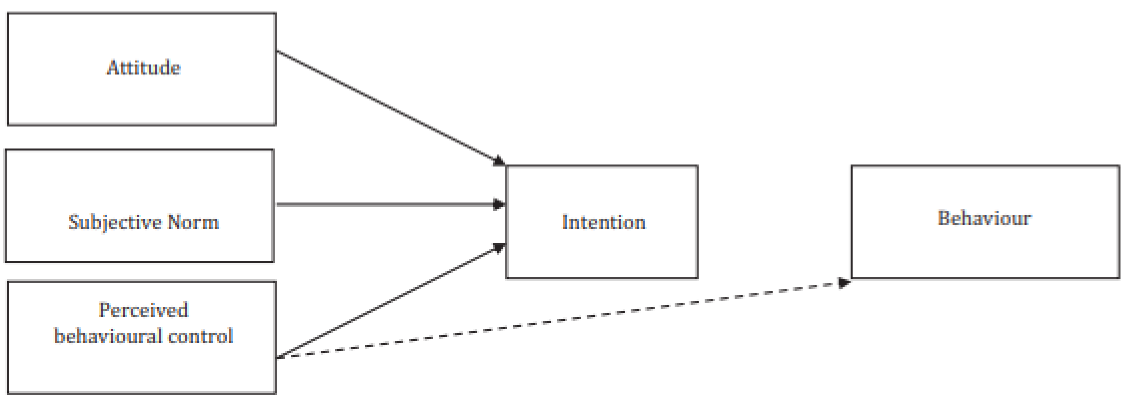
2.4.3 Alcohol Consumption

Some of the studies reviewed surmised that alcohol consumption while driving can lead to major crashes. Drobot et al. found that people were more likely to drive onto flooded highways if they had consumed alcohol (*22*). The study also found that alcohol consumption impaired a driver's decision-making process.

2.4.4 Macho Attitude

After a flood in January 2011 in which 35 people lost their lives and 78 percent of the state was declared a disaster zone, legislators in Queensland, Australia, initiated a movement with the saying "If it's flooded, forget it" (*23*). Although the program aimed to decrease the number of unintended drowning deaths, research to date estimates only marginal success at changing people's beliefs, attitudes, and actual drowning rates. Most fatalities are a result of individuals purposely driving through flooded areas (*24*). These fatalities are preventable, and the decision to undertake this type of risk-taking behavior is likely emotional, involving various social and motivational factors. Although mechanisms exist to help individuals understand why not to drive through a flooded watercourse, agencies must also pursue public health messaging to have an impact (*25*). Advertising countermeasures are often more cost effective and more manageable to implement, with clearly quantifiable constructs (*26*). However, the designs of many health advertising campaigns often neglect psychological theory.

Behavioral scientists recognize that the combined impact and the risk perception of all other factors (e.g., social, individual, environmental, etc.) impact people's decisions to drive into or turn back from floodwater. Behavioral scientists have used the Theory of Planned Behavior (TPB) to explain a driver's preparedness to take risks (see Figure 2-7). The research indicates that enlightening people's decision-making by employing educational creativities, regulating existing edicts, using advanced structural mechanisms, and regularly evaluating current strategies' efficiency are the best approaches for addressing driver behaviors.



Source: (*14*)

Figure 2-7. The Theory of Planned Behavior.

2.4.5 Distractions

Driving is mainly a visual task. Limited visibility situations such as fog, rain, or snow create several additional strains on the driver and reduce the driver's ability to collect necessary visual information. The driving task becomes more complicated when weather-correlated conditions of reduced visibility include wet surfaces. The effect of adverse weather situations on driver behavior has been a significant concern for many years and the subject of much research (*27*).

2.4.6 Role of Commuters

Many studies confirm that commuting plays a significant role in governing a driver's behavior (*17*). Altering this behavior will include educating the public about the seriousness of flood warnings and flood risks. Siegrist and Gutscher found that people could imagine what physical risk a flood carries, but they could not imagine the adverse effect of such an event (*28*). Research recommends that communicating risks also helps people to imagine the negative sensitive consequences of a flood. Community initiatives in Texas, such as the Texas Flash Flood Coalition and the "Turn Around, Don't Drown" program that work to educate local groups, including public school students, may help address the issue of driving into floodwater.

2.4.7 Inexperience

Grothmann and Reusswig proposed that previous experience is a critical factor for taking protective action to prepare households against flood loss (*29*). People in Denver who believed they did not live in an area where a flash flood may occur were more likely to state that they would drive through flooded roads (50 vs. 38 percent). In contrast, in Austin, a comparatively equal percentage of individuals indicated that they would drive through flooded highways regardless of whether they believed they lived in a location where a flash flood may arise. Yale et al. also suggested that many vehicle-related deaths during Hurricane Floyd involved people who were aware of flash flood cautions but did not feel threatened by the possibility of encountering dangerous floodwaters (*30*).

Ashley and Ashley (*9*) examined 4,586 flood fatalities in the United States between 1959 and 2005. They found that the number of deaths varied every year, with anomalously high years occurring with either tropical storm–produced floods or abrupt flash floods, often related to structural failures of dams or levees. Ruin et al. used cognitive mapping to classify several factors swaying motorists' flash flood risk awareness (*20*). Youth drivers underestimate flood risk, similar to drivers of lower-income groups and drivers with no children. The study found that individuals from urban areas underrate the risk of a car being swept away by water and are relatively more likely to drive or walk into flood conditions than people from rural areas. The general behavior reaction to harsh weather includes trip shortening, trip canceling, route changing, and more use of public transportation (*31*).

2.5 CRASH AND GEOMETRIC CHARACTERISTICS

This section discusses different crash and geometric characteristics that influence safety issues while driving.

2.5.1 Weather Conditions

Roadway-related crashes are among the five leading causes of death worldwide (*32*). Research documents that adverse weather is an important environmental factor leading to higher motor vehicle crash occurrences (*33*, *34*, *35*). Several studies have investigated the safety effects of different weather variables, including temperature (*36*, *37*), fog and smog (*38*), wind (*39*), and precipitation (*34*, *40*, *41*, *42*). Almost all these studies confirmed that precipitation has a significant impact on crash risk and frequency. However, this impact has various compounding factors, such as visibility impairment and road friction (*34*, *39*, *43*). Qui and Nixon's meta-analysis of previous studies indicated increases in the average relative risk of crash and injury rates by 75 to 84 percent for snow and 49 to 71 percent for rain (*44*). However, the wide confidence intervals of estimates based on multiple investigated studies revealed that these ranges could vary considerably. Black et al. pointed out that there is a statistically significant increase in crash (10 percent) and injury (8 percent) rates during rainy days, while higher precipitation intensities may increase the crash probability by up to 50 percent (*42*). A study by Hambly et al. confirmed this finding by demonstrating that days with moderate and heavy rainfall (≥ 10 mm) are associated with more crash risk (*45*).

Climatologically, flooding has been the second leading cause of weather-related fatalities, second only to heat, in the United States since 1987 (*46*). However, in 2015–2016, flooding was the leading cause of weather-related fatalities. The Ashley and Ashley study (*9*) found that during the period from 1959–2005, the average number of deaths per year due to flooding was approximately 97.6, with a median value of 81 deaths per year. The primary flood type associated with many of these fatalities was floods from heavy rain totals over a minimal time.

2.5.2 Season

Vehicle-related flash flood fatality rates appear to be associated with climate and topography. Khan et al. (*47*) established a spatial link between the number of weather patterns and crashes to determine that fewer fatalities happened in areas with dry weather, even when the population density was hig.. In one report related to flood fatalities, French et al. found that most flash floods from 1969–1981 happened during the warm season between July–September, with September being the peak mortality month (*48*).

2.5.3 Time of Day

Forty-one percent of vehicle-associated fatalities happened during nighttime. The darkness contributed to individuals not recognizing the floodwaters' fine points, such as depth, mere presence, or movement. The secondary crests of motor-vehicle-related fatalities occurred early in the morning (between 5 and 6 a.m.) and late evening (between 7 and 9 p.m.), indicating that people frequently refuse to change their daily routines (i.e., traveling to/from work) even with the existence of floodwaters on the road. In many cases, the deceased purposely drove through LWCs or bridges to reach their homes, possibly motivated by their self-reliance in their vehicles and driving capabilities in a familiar area (*9*, *22*, *49*).

It is hard to judge the speed and depth of flowing water while driving at night (*49*). A study by Maples and Tiefenbacher determined that 25 percent of fatalities occurred in the daytime, 14 percent at dusk/dawn, and 61 percent at night (*49*). Sharif et al. found similar results in their study, in which responders reported the time of events (346 of 471 incidents): 27 percent in the morning, 17 percent in the afternoon, and 56 percent at night (*50*). The type of flood can also be interrelated to the time of day. Flash flood losses occur mostly at night, while riverine losses are more common in the daytime (*51*).

2.5.4 Location

Jonkman and Kelman (*18*) found that 27 percent of flood deaths in European countries occurred in a vehicle. In the United States, 63 percent of flood deaths occurred in vehicles. The researchers surmised that the difference might be due to the understanding of flood risks in Europe, better warning methods or compliance with warnings in Europe, differences in the types of flooding, fewer LWCs in the European road network, or different reporting methods for flood mortalities.

2.5.5 Modeling Crash Type and Severity

Ye and Lord suggested that sample sizes may affect crash risk models and determined that small sample sizes can suggestively affect the development of consistent analytical models (*52*). Also, Yu and Abdel-Aty (*53*) and Yu et al. (*36*) attempted to examine the effect of contrary weather conditions using crash existence models. The authors advised that limited records of mortalities to investigate the harshness of crashes based on real-time weather data were among the main concerns of the study. The discrepancy between environmental data and crashes' temporal resolutions may cause considerable overestimation or underestimation of traffic crashes (*42, 54*). Both spatial and temporal resolutions of precipitation archives can significantly affect the comparative crash risk calculation, highlighting the significance of these parameters.

Researchers have used various time-based scales to analyze precipitation effects on traffic crashes. Bergel-Hayat et al. (*41*) used daily/monthly precipitation records, while in other research, daily precipitation records were used to investigate the effects of opposing weather conditions on crashes (*42*, *55*). Hourly radar images were used to analyze the consequences of precipitation based on sub-daily records compared to monthly and daily records.

2.5.6 Geomorphology

Geomorphologic and hydraulic data collection and analysis of river and stream channels in the Edwards Plateau enhanced the understanding of processes contributing to bedload transport and deposition at LWCs (*3*). These data facilitate modeling efforts and laboratory flume research. Geomorphology and channel hydraulics can be examined in the field and through computational analysis. Field research can further be subdivided into discrete measurements and continuous monitoring. The interpretation of geomorphologic and hydraulic data and the application of these findings in models and laboratory experiments could result in optimal design criteria for LWCs.

Geomorphic field research includes channel surveying, particle-size analyses, geophysics, and techniques to estimate bedload transport rates and scour. Surveys of channel cross-section and slope provide data for calculating shear stresses at the channel bed and the power of flows to mobilize and transport gravel. Surveys may also be used to compare pre-flood and post-flood channel conditions (*56*).

2.6 SUMMARY

This chapter provided a general overview of the LWC-related studies. Many states do not encourage LWCs unless the traffic volume is very low on those roadways. As flood-related crashes and events began increasing in recent years, a handful of studies examined different risk factors and countermeasures associated with LWCs. This report documents the state-of-the-art practices for LWCs. The findings of this review of the literature show that, in general, past works have supported the notion that LWCs are low-cost solutions for roadways with low traffic volume. Additionally, several successful countermeasures and design alternatives from other states show potential to be implemented in Texas.

Chapter 3. STATE-OF-THE-PRACTICE SURVEY

3.1 INTRODUCTION

The researchers surveyed TxDOT and other DOT staff to assess the state of the practice of the current LWC inventory, including:

- LWC design and countermeasure implementation protocol.
- Criteria and methods for diagnosing problems and choosing advanced alternatives.
- LWC inventory and management approaches.

3.2 SURVEY OF TXDOT AREA OFFICES

From a pool of TxDOT area office personnel, 50 participants completed the survey. This section highlights some key findings of the survey of TxDOT area offices. Figure 3-1 illustrates the Texas map showing the responses received from each district.

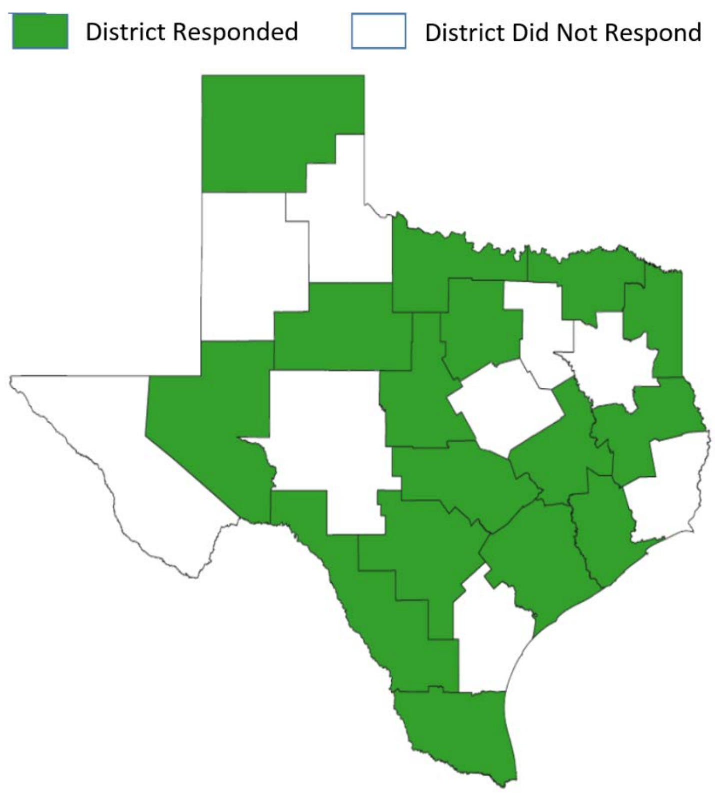


Figure 3-1. Survey Responses by TxDOT Districts.

The survey contained multiple questions related to LWCs, such as whether the area office maintains an inventory of the data or developed any protocol or countermeasures. Appendix A provides the questions the researchers used in the survey.

Table 3-1 provides a summary of the response rate from the TxDOT districts. The table shows that 88 percent of respondents indicated that the area offices do not have LWC inventories. In response to Questions 4 and 5, 44 percent of respondents indicated that the area offices have developed LWC design and countermeasure implementation protocols. The responses regarding problem diagnosis and alternatives suggest that most area offices (around 64 percent) have not developed any specific criteria or methods. The researchers found similar negative responses regarding consideration of location/scenario characteristics for LWC implementation.

Figure 3-2 shows the percentage distribution of responses for Questions 2, 4, 6, and 10 related to inventory data of LWC, countermeasures, design alternatives, and major considerations.

3.2.1 Inventory of LWCs and Flood-Prone Roadways

The researchers asked whether area offices have existing inventories of their LWCs. Those with a yes response to this question either uploaded a document on relevant field studies or shared the contact information of the supervisors who are working in that area for further details on inventory data.

3.2.2 LWC Protocols and Countermeasures

In terms of protocol options, the respondents were split with respect to the implemented protocols and countermeasures. Figure 3-3 shows different protocols used in the LWC locations. The researchers found that barricades and warning signs are the most commonly used protocols. Table 3-2 lists related individual responses received from different districts.

3.2.3 LWC Management Alternatives

Regarding LWC management alternatives, the respondents provided a range of responses. Figure 3-4 shows the management issues that area offices reported associated with LWC locations. The researchers found that debris blockages are common at many LWCs. Table 3-3 lists related individual responses received from different districts.

3.2.4 Factors Considered in Developing and Implementing LWC Treatment Strategies

Agencies need to understand the location or scenario characteristics considered when selecting specific countermeasures or design alternatives. Table 3-4 lists individual responses from different area offices concerning the factors they consider in identifying and deploying LWC treatment strategies.

Table 3-1. TxDOT Response Rates to Survey Questions.

Questions	Number of "Yes" Responses	Number of "No" Responses	Did Not Respond
Does your Area Office have an inventory for low water crossings?	6	44	0
Has your Area Office developed low water crossing design and countermeasure implementation protocols (i.e., barricades, flood sensors, passive signs, and active warning devices)?	22	24	4
Has your Area Office developed any criteria/methods for diagnosing problems and developing alternatives concerning low water crossings?	10	32	8
Please list the different low water crossing countermeasures your Area Office has implemented (i.e., barricades, flood sensors, passive signs, active warning devices). For each of the listed countermeasures, please provide as much feedback as possible about their functionality, installation, maintenance, operation, etc. You can also upload files of the developed criteria as an attachment if preferred.	33	17	0
Based on your experience, how would you categorize the success (or failure) of both passive and active devices utilized by your Area Office to improve visibility and alert motorists of flooding events at low water crossings?	34	16	0
When selecting different low water crossing countermeasures for implementation, does your Area Office consider location/scenario characteristics? (For example, you implement countermeasure Type A for scenarios that are Type 1 and Type 2.) If so, would you be able to share the main reasoning for your choices?	8	55	9
How does your Area Office prioritize the characteristics of locations where future device deployment is most needed?	30	20	0
Are there any other relevant issues or ideas concerning low water crossings that you would like to share/discuss (i.e., design considerations, operational challenges, need for connected vehicle technologies, and smartphone apps for flood hazard warning)? These can be issues you are already facing or suggestions that you identify as possible solutions for low water crossing locations.	20	30	0
Are there any other comments you would like to share with the Project Team? If so, please feel free to include your comment(s) in the comment box below.	2	48	0

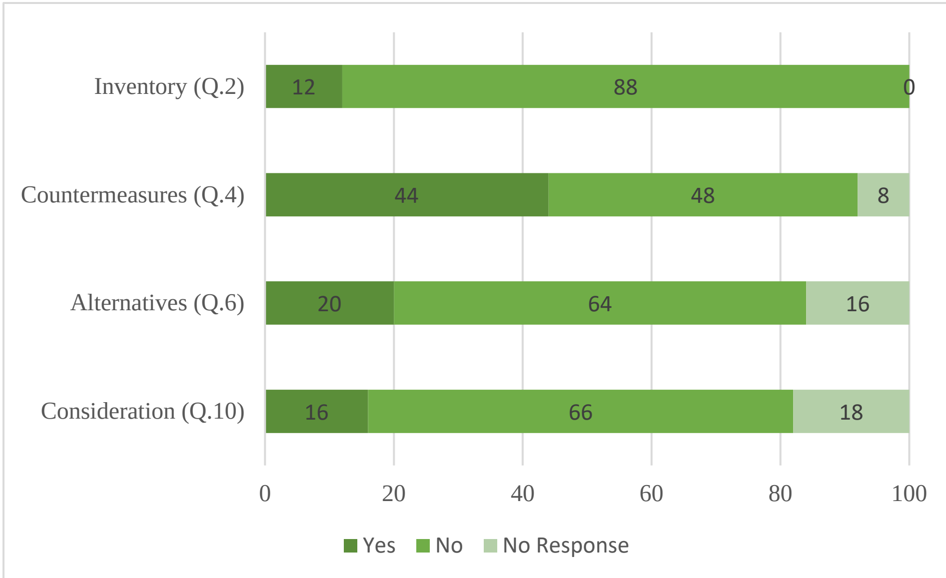


Figure 3-2. TxDOT Survey Responses for Questions 2, 4, 6, and 10.

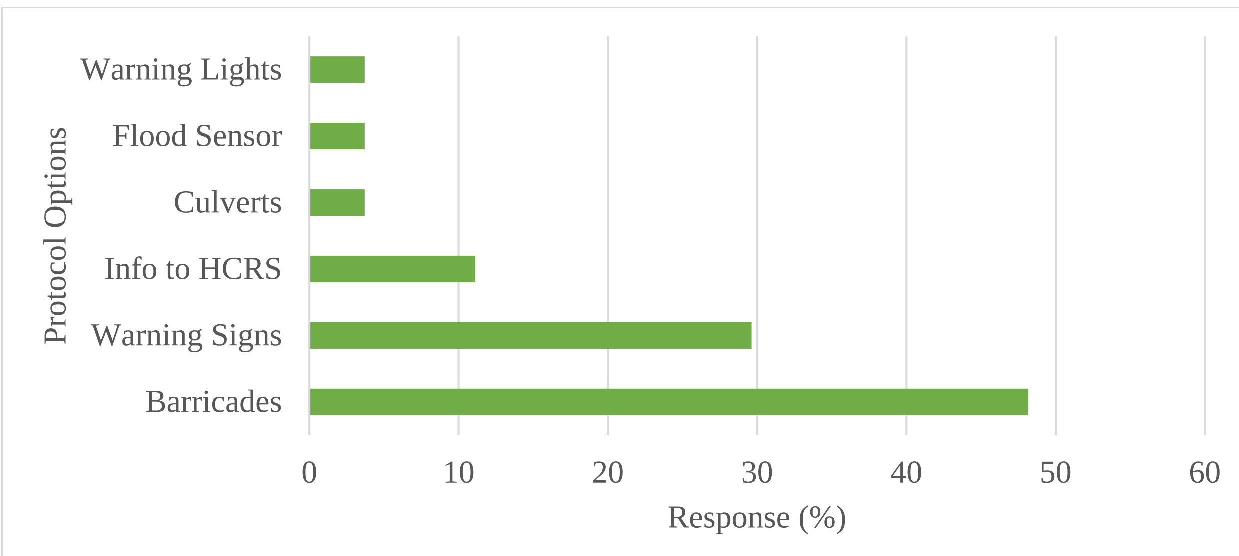


Figure 3-3. Types of Protocol and Countermeasures Identified by TxDOT Survey Respondents.

Table 3-2. Individual TxDOT Responses for Protocol and Countermeasures Survey Question.

TxDOT Area Office	Response	Solution
West Harris	IH 610 @ Westpark road, there are gates if the pump house cannot keep pumping the water off the road. These gates are open and shut manually by employees.	Barricades
Gainesville	We install standard Warning Signs (ROAD MAY FLOOD) at problem areas. We will place barricades and additional signs once a problem arises.	Warning Signs, Barricades
Lufkin	Our location has areas that are not designated as low water crossings but regularly flood during heavy rains. We can close the road and place barricades with a road closed sign if needed. We also utilize employees with pickups and strobes to warn the public of water across the roadway. Most of our flooding locations run down in a few hours. We do have some creek bottoms that flood and last up to two days occasionally.	Warning Signs, Barricades
Mt. Vernon/ Sulphur Springs	Place barricades in advance of the spot where water crosses the road and close the road down until water gets off the road. Enter the information into HCRS.	Barricades
Hopkins County	In low-lying areas that are prone to flooding, we close the roadway with signs and barricades. We also enter the closure in HCRS.	Warning Signs, Barricades, Info to HCRS
Seymour and Archer City	We put water over the road signs up during flooding events. On major roads, we have employees sit at these sites warning motorist. We put all our flooded roads on HCR.	Warning Signs
Gainesville	When flood events happen, we deploy warning signage and close the roadway to the low water crossing with barricades and channeling devices. Input required information in HCR to warn the traveling public.	Warning Signs, Barricades, Info to HCRS
Yoakum	Each maintenance section knows these areas in my area and typically prepositions signs and barricades before a significant rainfall event. There are also permanent signs at several locations advising of possible flooding conditions.	Warning Signs, Barricades
Weatherford	We have built a Barricade trailer for quick response to close high-water areas. That along with a Road Closed for High Water TCP, we can respond quickly to any concerns.	Barricades
Big Spring	Passive Signage and Barricades.	Warning Signs, Barricades
Midland	We have just raised the grade and add culverts when we want to eliminate a low water crossing.	Addition of Culverts

TxDOT Area Office	Response	Solution
Gainesville	We use barricades during flood events and have flood gauge signs in place.	Warning Signs, Barricades
Brackettville Section/Del Rio	If a low water crossing has more the six inches of water, we close the crossing. The road is then closed, and the information is entered HCRS and sent to the district PIO.	Info to HCRS
Mineola	Barricade and close road.	Barricades
Eastland	We have automatic gates on IH 20 frontage roads at a low water crossing. Maintenance supervisors also know where storm water typically overtops the roadways. They put out barricades and continuously monitor during events.	Automatic Gates, Barricades
Texarkana	Flood sensor with solar panel acting as an active warning device on US 82, Bowie Co. Our District Traffic section installed the flood sensor. I don’t know the details.	Flood Sensor
Hondo	We pre-staging our barricades. Some flashing warning lights in place.	Barricades, Warning Lights

Note: HCRS (also HCR) = Highway Condition Reporting System.

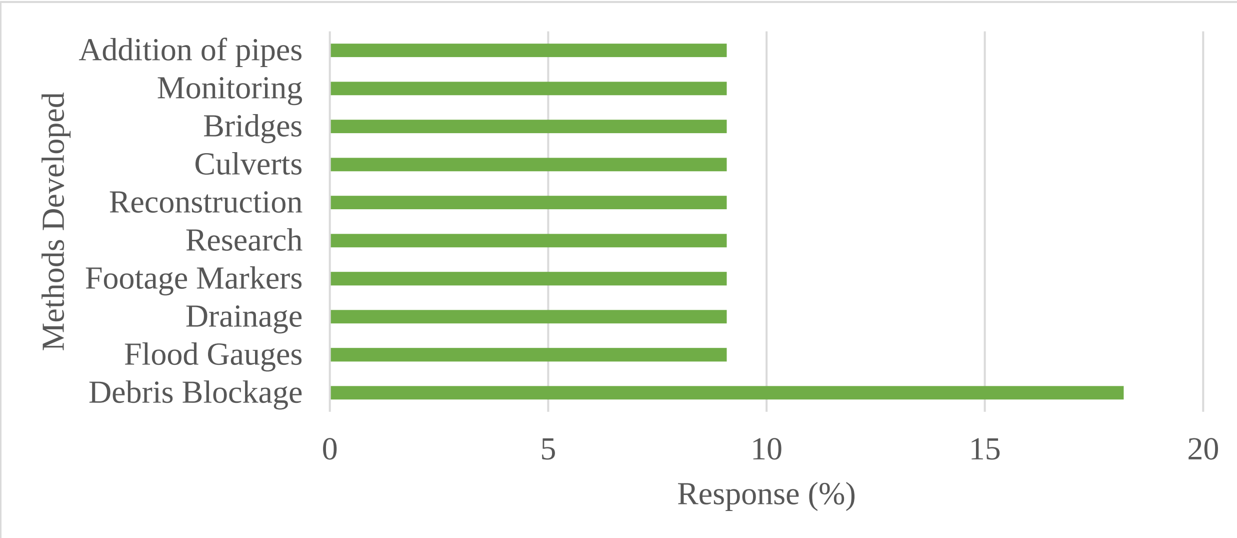


Figure 3-4. Types of LWC Management Alternatives Identified by TxDOT Survey Respondents.

Table 3-3. Individual TxDOT Responses for LWC Management Alternatives Survey Question.

TxDOT Area Office	Response	Solution
West Harris	We have installed flood gauges on all roads that pass under a bridge.	Flood Gauges
Lufkin	In areas that flood regularly, we consider adding additional drainage, raising the roadway, and removing silt and debris from drainage structures.	Drainage, Debris Blockage
Seymour and Archer City	We have footage markers that let people know how deep the water is at locations with a history of flooding.	Footage Markers
Gainesville	Monitor the condition and debris blockage, work to keep barrels clean.	Debris Blockage
Weatherford	We discuss areas of concern and look into ways to rectify the high-water crossing areas.	Research
Big Spring	We improve low water crossings with all widening, mill and overlay, or any other reconstruction projects. We improve the crossings with either culverts or a bridge as design dictates.	Reconstruction
Gainesville	We monitor low water crossings for rising water during flood events.	Monitoring
Eastland	We have only discussed replacing several low water crossings in McCulloch County that frequently overtops. Discussion is mainly about adding several pipes to pass a 2-year or 5-year storm since it is a low volume FM.	Adding Pipes

Table 3-4. Individual TxDOT Responses for LWC Considerations Survey Question.

TxDOT Area Office	Response	Comment
Gainesville	No	Hard to have countermeasures when we have followed TxDOT guidelines in our response to flooded areas.
Lufkin	Yes	In areas that flood on rare occasions and floodwaters are shallow, raising the roadbed is an option that helps alleviate problems. We also have flood-prone areas where we have installed new and larger bridges, allowing more clearance for floodwaters.
Mt. Vernon/ Sulphur Springs	Yes	When we have a Farm to Market road go underwater, we just put up barricades and road closed signs, but when we have a State Highway go underwater, we set up message boards and detour signs along with additional warning signs.
Seymour and Archer City	Yes	Our resources are focused on our highways with the most traffic and secondary roads after.
Sulphur Springs	No	Barricades and signs are the only measures we use at all locations.
Yoakum	No	The measure is typically the same during a flood event.
Brackettville Section/Del Rio	No	Other than closing the road, we do not implement any countermeasures routinely.
Eastland	Yes	We mainly look at the importance of the roadway and the volume of traffic for each scenario.
Lampasas Co. Maint./ Brownwood	Yes	We discuss and put out extra temporary water over road signs and road closed ahead signs and barricades.
Hondo	No	We don’t have any system for improvements.

3.2.5 Traffic Control Countermeasures at Flooded LWCs

The researchers asked TxDOT area offices to identify common traffic control strategies deployed at LWCs during a flooding event. Figure 3-5 illustrates the percentage distributions of the key countermeasures identified. Barricades and flood gauges are the most used countermeasures. Table 3-5 lists individual responses from different area offices for Question 8.

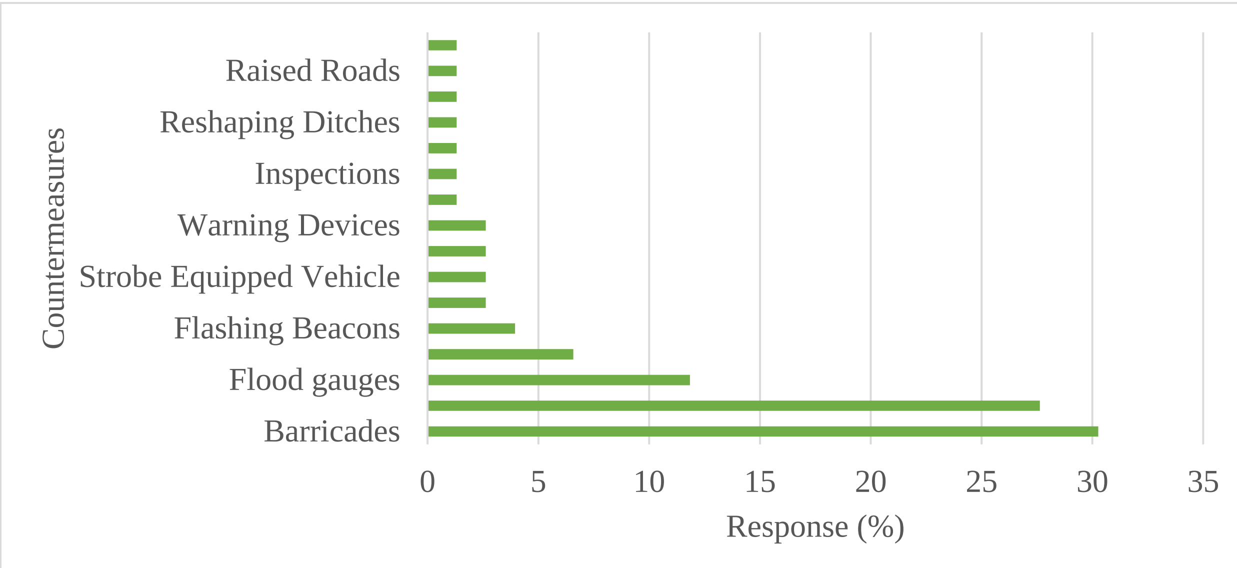


Figure 3-5. Types of Traffic Control Devices Deployed by TxDOT Area Offices at Flooded LWCs.

Table 3-5. Individual TxDOT Responses for Traffic Control Countermeasures Survey Question.

TxDOT Area Office	Response	Solution
Bryan	Our office uses barricades and warning signs at our crossings.	Barricades, Warning Signs
Graham	We use barricades mostly with ROAD CLOSED signs and WATCH FOR WATER ON ROAD signs.	Barricades, Warning Signs
West Harris	We use Flood gauges for our underpasses. We located these signs at the bottom of the overpass, and we install advanced warning signs before the gauge. We also locate gates on both sides of the underpass of IH 610 @ Westpark road.	Flood Gauges, Warning Signs, Barricades
Brenham	In Burleson County, the area crews will load WATCH FOR WATER OVER ROAD signs if we know that we might have flooding. If there is water over the road that is only (maybe 1"–2" or a little more), we will place WATCH FOR WATER OVER ROAD signs and stage trucks on both sides of water with their strobes on to advise the traveling public. If the crossing is not traversable, we will place barricades on both sides of the water across the road and set a ROAD CLOSED sign on a Buster behind the barricades, up from the water. We also place ROAD CLOSED AHEAD signs warning the public of the closure. We also enter the location in the Highway Condition Reporting (HCR) system.	Warning Signs, Staged Trucks, Barricades, Info to HCRS
Graham	I'm not aware of any on-system low water crossings in my area. We have short roadway sections that occasionally function as low water crossings when overtopping occurs. These locations have permanent warning signs WATCH FOR WATER OVER ROAD and some flood gauges.	Warning Signs, Flood Gauges
Gainesville	We do not have a "list" of areas on file. We simply know which areas give us problems. Some areas need more work than just maintenance can provide. Maintenance forces can clean up other areas as time permits. The only mainstay on problem areas is the standard warning signs. We will deploy barricades, roll-up signs, and personnel as issues arise.	Cleaning, Warning Signs, Barricades
Lufkin	Barricades—Red barricades with ROAD CLOSED signs. These are used in extreme situations only. Employees with strobe equipped vehicles—our most common response to high water. This response allows the public someone to ask questions to make sound decisions about crossing flooded roadways. In most instances, we advise travelers not to enter flooded areas. The response requires scheduling employees for shiftwork in extended flooding events.	Barricades, Strobe-Equipped Vehicle

TxDOT Area Office	Response	Solution
Mt. Vernon/ Sulphur Springs	We have permanent ROAD MAY FLOOD signs at all the locations that water historically overtops the road. During heavy rain events, we keep monitoring the roadways, and when the water gets over the road, we close the road by placing barricades in advance of the water crossing with a ROAD CLOSED sign mounted just behind the barricade. The barricades work well because they are visible and letting people know that the road is closed. Unfortunately, people just move them out of the way, or they drive around them. We have to keep checking the barricades to make sure that they haven't been moved.	Warning Signs, Regular Monitoring, Barricades
Seymour and Archer City	Signs, barricades, message boards, HCR, and pickups with strobes staffed by employees.	Warning Signs, Barricades, Strobe-Equipped Vehicles
Hopkins County	We have warning signs in low areas advising traffic that the roadway may flood.	Warning Signs
Gainesville	When flood events happen, we deploy advanced warning signage and close the roadway to the low water crossing with barricades and channeling devices. We also input the required information in HCR to warn the traveling public.	Warning Signs, Barricades, Info to HCRS
Sulphur Springs	Barricades, water depth gauges, advanced ROAD MAY FLOOD signs.	Barricades, Flood Gauges, Warning Signs
Yoakum	Barricades and Signs—Each Maintenance Sections knows its flood-prone areas. They inspect and monitor known rainfall events and position these signs when needed. We also place the condition in the HCRS System. Before opening, we inspect the bridge as much as possible due to the continued water flow for potential issues and take corrective actions if possible. Otherwise, the bridge remains closed until expert staff in our Bridge Division perform further investigation.	Barricades, Warning Signs, Regular Monitoring, Info to HCRS, Inspections
Weatherford	Adding bigger pipes, addressing the areas during a construction project, reshaping ditches.	Adding Pipes,

TxDOT Area Office	Response	Solution
		Reshaping Ditches
Hondo	Permitted signs and gauges. Barricades for short term countermeasures.	Warning Signs, Flood Gauges, Barricades
Kerrville/ Uvalde Maintenance	Barricades, Flood Sensors, and warning signs.	Barricades, Flood Sensors, Warning Signs
Eastland	In this county, we will use barricades if the water gets too deep. We have flood gauges at the low water crossings. We also have advanced warning signs at them.	Barricades, Flood Gauges, Warning Signs
Sherman	We do not have any “low water crossings” in my area. We have several locations where a 25-year or higher flood event will go over the roadway. The maintenance sections well know these locations. We place Type III barricades and advanced signing ahead of the closure. There is usually a flood gauge at these locations with advanced signing as well.	Barricades, Warning Signs, Flood Gauge
Big Spring	We place pop-up signs and or placard cones in areas where water depths don’t exceed a few inches. This treatment works for the majority of our low water crossings. This measure works well to slow the traffic and alerts them to look for water on the roadway. Barricades are called for only occasionally in areas where we know the water will exceed a few inches. The flow in these areas can get high enough to see no longer the roadway or move a vehicle. Even though we respond to these areas before the flow becomes a danger, the motorists can move or drive around barricades.	Warning Signs, Barricades
Marshall	We do not have any low water crossings. We do have roadways where the existing drainage structure will occasionally be inadequate to handle a particular flood event’s runoff. In those instances, we station TxDOT vehicles with warning lights at those locations to warn motorists and monitor until the flooding subsides.	Vehicle Staged
Midland	We have only raised the road and added culverts to eliminate low water crossings.	Culverts, Raised Roads
Gainesville	We use barricades during flood events and also have flood gage signs in place.	Barricades, Warning Signs

TxDOT Area Office	Response	Solution
Fort Stockton	We have existing flood gauges and warning signs that I am in the process of updating to current standards and resigning if old/damaged. We just started this initiative a few weeks ago.	Flood Gauges, Warning Signs
Brackettville Section/Del Rio	Place barricades and close road.	Barricades
Fort Stockton	Currently, we have flood gauges, dip signs, WATCH FOR WATER ON ROAD signs.	Flood Gauges, Warning Signs
Mineola	Barricade and close road, post information on Drive Texas.	Barricades, Info to HCRS
Junction	We place barricades manually to close the roadway, and we submit closure information to the HCRS.	Barricades, Info to HCRS
Eastland	Barricades and active warning devices. To my knowledge, these have worked well for us in the past.	Barricades, Warning Devices
Del Rio	Low water flashing beacons.	Flashing Beacons
Lampasas Co. Maint./ Brownwood	We have advanced permanent warning signs and flood gauge signs in place. During flood events, we also station flaggers at locations until water levels are safe for the public. We also set out extra temporary signs during events for water over road and road closed ahead and barricades.	Warning Signs, Flood Gauge, Flaggers, Barricades
Texarkana	We use flood sensors acting as active warning devices. The sensor will activate the flashing beacon as soon as the water goes over the road.	Warning Sensors, Flashing Beacon
Greenville	Barricades.	Barricades
Hondo	Barricades are the primary measure for closing roads for flooding. We use flashing warning lights at some locations. We identify closures in the HCRS.	Barricades, Warning Lights

3.2.6 Degree of Success (or Failure) of Passive and Active LWC Devices

The researchers asked TxDOT area offices to categorize the effectiveness of the implemented countermeasures at LWC locations. Figure 3-6 shows the success rate is higher than the failure rate. Table 3-6 lists individual responses from different area offices on categorizing the success of various LWC countermeasures.

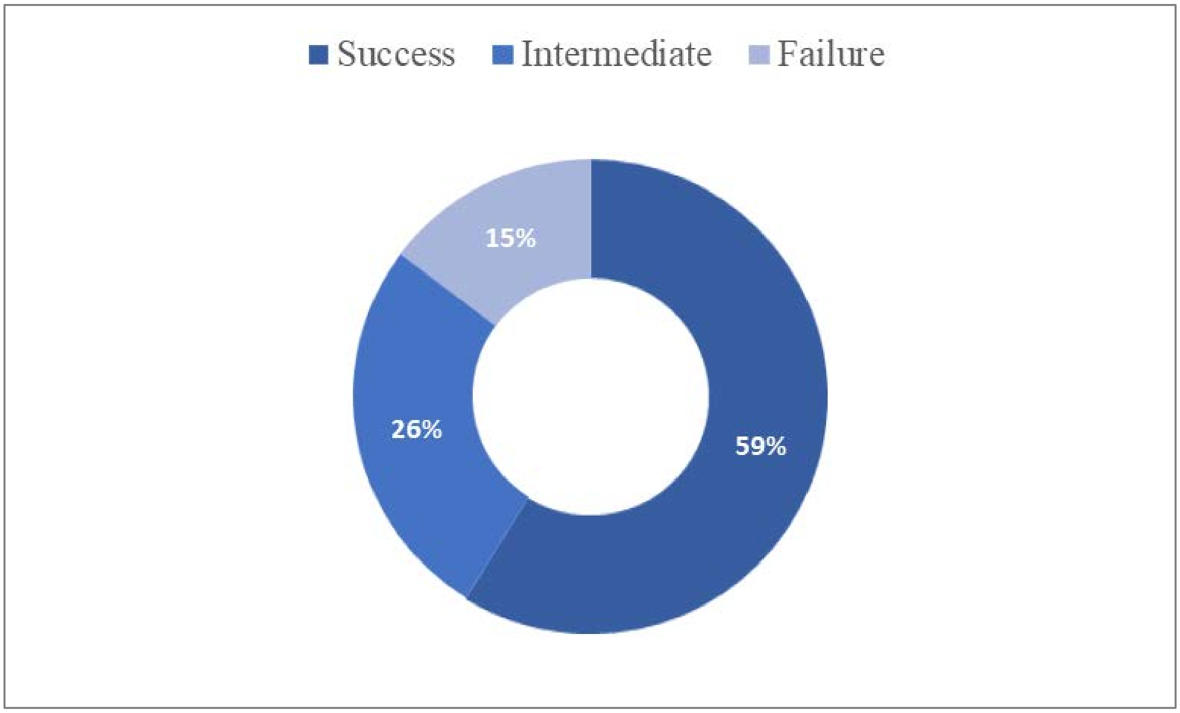


Figure 3-6. TxDOT Responses to Degree of Success of Passive and Active LWC Devices Question.

Table 3-6. Individual TxDOT Responses for Degree of Success Survey Question.

TxDOT Area Office	Response	Comment
Bryan	Success	We have not any issues getting our message to the motorists.
Graham	Success	We have great success with our methods of directing traffic.
Sulphur Springs	Intermediate	Typically, if the water is over the road, we will close the road with barricades.
West Harris	Intermediate	It has worked, but the traveling public does not always pay attention to the signage.
Graham	Success	I’ve been here for over five years, through approximately five significant flooding events. We’ve had a few rescues from flooded vehicles and zero fatalities. There hasn’t been an instance where a driver encountered water over a roadway unexpectedly.
Gainesville	Failure	Failure if an actual person is not sitting on the location at all times. People simply drive around barricades, ignore signs, and continue. We have the same problem from time to time, even when a TxDOT rep staffs the high-water area.
Lufkin	Success	Our methods work very well to let the public know when the roadway is flooded. We occasionally still have drivers choose to enter flooded roadways. Sometimes, this results in vehicles being washed off the roadway due to the water and driver error.
Mt. Vernon/ Sulphur Springs	Intermediate	I think we have succeeded in letting people know that water is over the road and the road is closed, but we have failed because people can move or go around the barricades.
Seymour and Archer City	Failure	They don’t slow down in work zones, and the public doesn’t slow down in flooding.
Hopkins County	Intermediate	The road closure methods that we perform during flooding events seem effective as long as motorists respect our devices. Sometimes our barricades are moved by the public. We have two particular areas of concern on the Sulphur River. In both areas, timber debris and silt are causing severe issues with the channel, which seriously impacts our system. One location is at the Hopkins/Delta county line on FM 71. The other location is at the Franklin/Red River county line on SH 37. Log and debris jams in the river channel are causing the water flow to redirect.
Austin District Operations	Success	The experience has been positive. We execute the work based on priority.
Gainesville	Success	We have had good luck with warning the public with signs and barricades, and HCR reports. Also, we have had good luck with communications between local law enforcement agencies.
Sulphur Springs	Intermediate	In some areas, they work well, but in other areas, they drive around them.

TxDOT Area Office	Response	Comment
Yoakum	Intermediate	Work well with residents; however, our oil-field community will more frequently disregard the signs and barricades.
Hondo	Success	Short-term countermeasures are effective when installed in time.
Kerrville/ Uvalde	Failure	Very Poor on Flood Sensors.
Eastland	Success	I believe that we have adequate signage and the flood gauges help also.
Sherman	Success	I feel we are meeting expectations to patrolling during heavy rain events and closing roadways as needed.
Big Spring	Success	Most all of the low water crossings in our area are in rural areas. The traffic is all local, and they are familiar with these areas and know to detour after significant rain events. I would consider our method to be a success.
Marshall	Intermediate	The use of TxDOT vehicles with warning lights works well for visibility and local warning. However, this is only a reactive measure. The roadway could have been flooded for minutes or even hours before we are aware and able to place a warning vehicle at the site. Often, the local traffic will ignore our warning and proceed through the flooded area at their own risk.
Midland	Success	I think it has helped motorists even during low rain events.
Gainesville	Success	I think the measures that are in place for the low water crossing work perfectly.
Fort Stockton	Success	We have all passive due to the remoteness and small amount of rainfall in west Texas.
Brackettville Section/Del Rio	Success	I believe the current protocols have been a success.
Fort Stockton	Success	The signs we currently have work good we also monitor roads when it rains.
Mineola	Success	Successful.
Del Rio Area/ Maintenance Office	Success	We don’t have any on our locations.
Junction	Intermediate	The manual system to place barricades is labor-intensive and not 100 percent effective. The traffic will push the barricades off of the road and drive around.
Del Rio	Intermediate	We need the Traffic Safety Divisions to design a Traffic Control Plan (TCP) for road closures due to flooding.
Eastland	Success	To my knowledge, the automatic gates work well. People generally don’t try to drive around them. Barricades with a TxDOT employee monitoring the crossing also generally works well for us.

TxDOT Area Office	Response	Comment
Lampasas Co. Maint./ Brownwood	Success	We have low water crossings on low volume roads; all advanced warning seems to be working well. We also station flaggers at locations during events until the water level is safe for the traveling public. Also, set out water over road signs and road closed ahead signs and barricades.
Texarkana	Success	The flood sensor has worked well to alert motorists of water crossing the roadway. We usually have someone in a pickup with blue and amber lights on the shoulder or turnout area to alert motorists of roadway flooding ahead at other low water crossing locations. When severe flooding occurs, we will put up barricades as requested or needed.
Greenville	Failure	Not very effective. Drivers move our barricades and continue traveling across the low water, sometimes resulting in their vehicles washing into a ditch.
Hondo	Failure	We need to utilize more flood sensors. We need an inventory of low water crossings. The barricades are very reactive based on experience or calls from public or law enforcement.

3.2.7 Prioritization Criteria

The researchers asked the TxDOT area offices about their prioritization criteria of locations where future devices are most needed to be implemented. Figure 3-7 shows TxDOT's responses on individual districts prioritize their decisions about when to close LWCs. Most respondents responded that they already knew their areas of concern. Table 3-7 lists individual responses from different area offices.

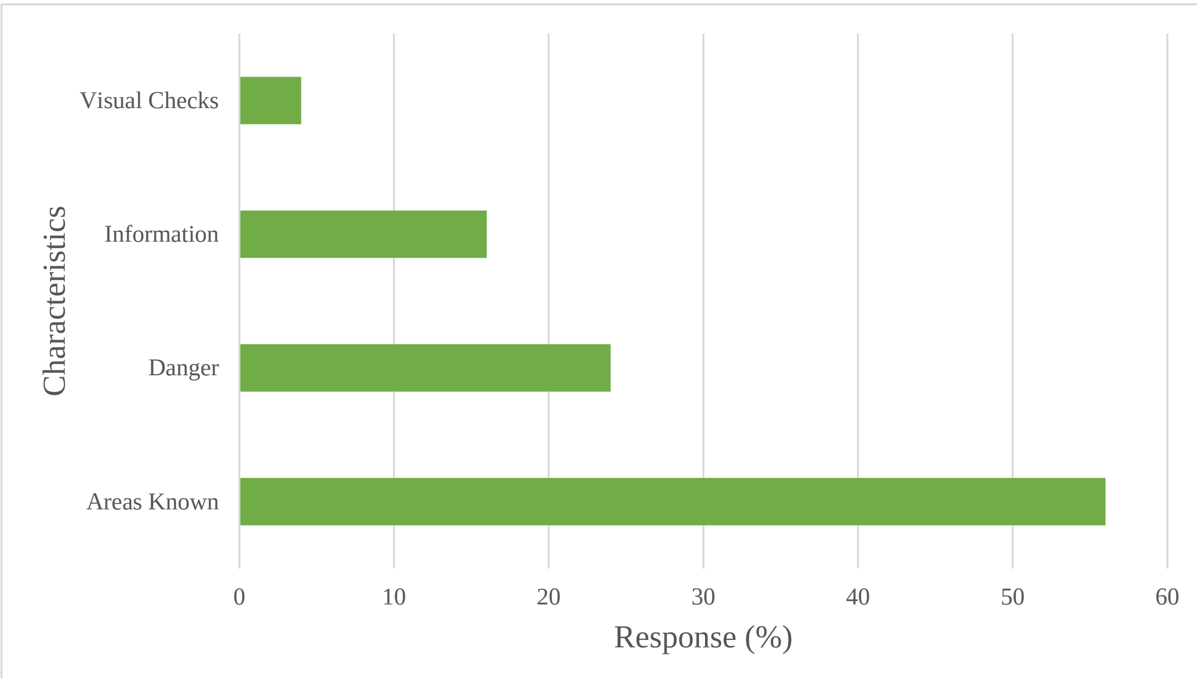


Figure 3-7. TxDOT Responses to Prioritization Criteria Question.

Table 3-7. Individual TxDOT Responses for Prioritization Criteria Survey Question.

TxDOT Area Office	Response	Solution
Bryan	Visual checks to determine if priorities need to be changed.	Visual Checks
Graham	We know are problem areas that flood.	Areas Known
Sulphur Springs	We have not yet.	N/A
West Harris	Most of the roads are existing condition, so we watch the weather and deploy needed traffic control devices for roads that have an issue with flooding.	Deploy Traffic
Brenham	The areas that we know will probably flood first.	Areas Known
Gainesville	We assess the need for more warnings on a case by case basis.	Areas Known
Lufkin	Funding available, age of structures, frequency of flooding, accidents or incidents at locations.	Information
Seymour and Archer City	Roads with a history of flooding have permanent signs warning the public of the possible danger of water over the road.	Danger
Hopkins County	We are familiar with our areas of concern. We monitor our locations and deploy accordingly.	Areas Known
Austin District Operations	1. Frequency of flooding/water ponding; 2. Duration of flooding; 3. Flooded related crashes (especially fatality accidents); 4. Type of LWC; 5. Roadway Characteristics; 6. Traffic Volumes; 7. Local operation and maintenance experiences.	Danger
Gainesville	We monitor any potential problem areas during flood events and prioritize based on threat.	Danger
Mt. Vernon/ Sulphur Springs	We take care of all major roads first where traffic is the heaviest.	Areas Known
Weatherford	Information is gathered and discussed as a group.	Information
Hondo	By the severity of the storm/flood.	Danger
Kerrville/Uvalde Maintenance	The number of incidents, the amount of traffic, the frequency of flooding, and the distance for TXDOT maintenance employees to respond.	Danger
Eastland	I am unsure.	N/A
Sherman	Based on the occurrence and probability of flooding.	Danger
Big Spring	Each section has a priority list that is based on experience.	Areas Known
Marshall	Our responses are based on experience from previous flood events and are mostly reactionary to the event.	Areas Known
Midland	We look at the type of roadway we also take into account areas where we have had a history of accidents.	Areas Known

TxDOT Area Office	Response	Solution
Brackettville Section/Del Rio	We decide based on traffic and how often the road is closed due to flooding.	Areas Known
Fort Stockton	We monitor the roads for flooding.	Areas Known
Del Rio Area/ Maintenance Office	We are looking into the areas we have with our AE and District Maintenance.	Areas Known
Junction	Not in place at this time.	N/A
Laredo	Based on the tier of the roadways.	Areas Known
Eastland	Generally prioritized by how often the location overtops, roadway type, and complaints received or other issues.	Areas Known
Lampasas Co. Maint./ Brownwood	Depends on how many flooding issues that the maintenance sections report and need help with concerns.	Information Received
Texarkana	I am not aware of a plan in place to address the issue.	N/A
Greenville	We look at historical locations that have flooded and under what circumstances and focus our efforts there.	Areas Known
Hondo	Based on motorists getting stuck or accidents.	Information

Note: N/A = not applicable.

Area office respondents also shared other relevant issues and ideas concerning LWCs, such as design considerations, operational challenges, the need for CV technologies, and smartphone apps for flood hazards in their responses. Figure 3-8 shows warning lights, graphical user interfaces (GUIs), and log jams to be the most frequent issues identified. Table 3-8 lists individual responses from different area offices.

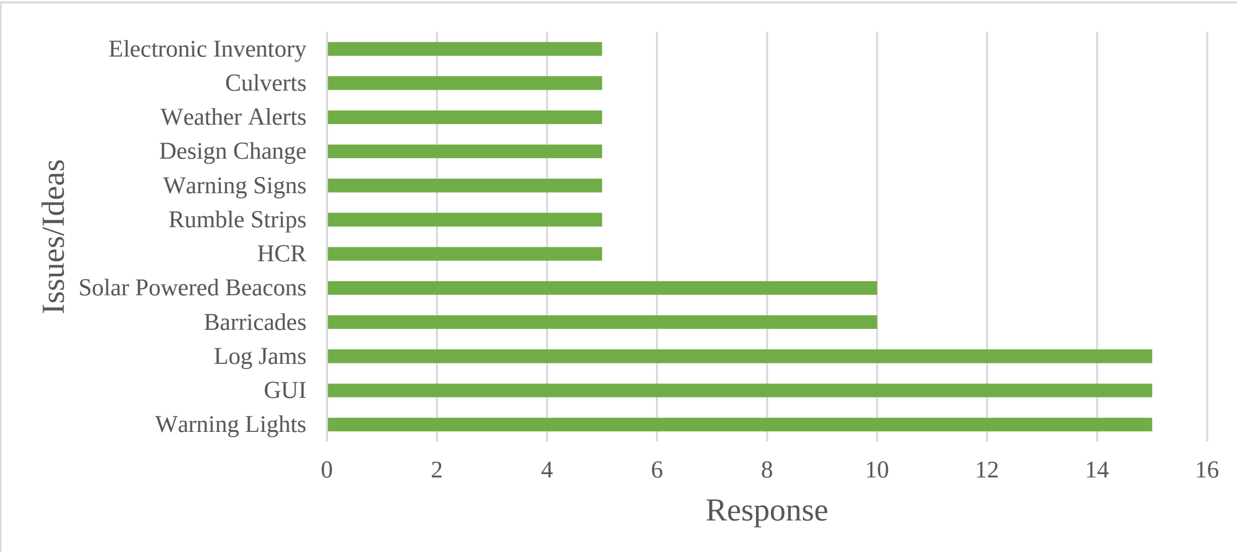


Figure 3-8. TxDOT Responses to Other Relevant Issues and Ideas Question.

Table 3-8. Individual TxDOT Responses for Requests for Other Relevant Issues and Ideas.

TxDOT Area Office	Response	Solution
Graham	HCR works great for notifying the traveling public.	HCR
Gainesville	Self-closing gates with warning lights on problem areas. Similar to railroad crossings.	Barricades Warning Lights
Lufkin	I believe installing rumble strips and flashing lights with warning signs could be the best options for low water crossings.	Rumble Strips Warning Lights Warning Signs
Seymour and Archer City	When you get a large amount of rain, there is not much you can do.	N/A
Hopkins County	As a maintenance supervisor, I would always like to see any design changes or features that can minimize the possibility of flooded roads.	Design Change
Gainesville	A major issue that causes most of our flood event problems is the amount of debris upstream that washes down and clods our structures, creating the overflow.	Log Jams
Mt. Vernon/ Sulphur Springs	Log jams are some of our problem areas. I feel like if we removed them, it would help creeks to flow better.	Log Jams
Yoakum	Warnings tied to road closures or flood, like weather alerts, would augment TxDOT signs and barricades—an alert to a mobile device when you are in the proximity of a flooded area.	Weather Alerts
Austin District Operations	We suggest that a Geographical User Interface (GUI) be developed based on the LWC information presented in the ArcGIS inventory database. This GUI would allow TxDOT Austin District office and the various Area and Maintenance Offices to 1) retrieve and document information about LWC locations and flood events, 2) display exhibits or graphics for information purposes, 3) edit the database to keep LWC information up to date, and 4) provide information to the public.	GUI
Eastland Area Office	At a few of our low water crossings, I believe if we put in culverts and raised the road's profile, it would do away with the low water crossing.	Culverts
Sherman	We use a simplified approach. Again, we do not technically have any low water crossing, but we have locations that flood a couple of times per year.	N/A

TxDOT Area Office	Response	Solution
Marshall	I would love to see a system that utilizes either smartphones, in-car GPS, or other systems to warn motorists of flood conditions ahead. The GPS already knows where your location and your direction of travel. If that information could be tied to known flooding areas and relayed in real-time that would be great.	GUI
Midland	I can't think of any.	N/A
Fort Stockton	In west Texas, we have inadequate cell coverage. This type of device would be very limited for our region. I am not sure if a WIFI service could be available or some sort of booster. It wouldn't serve many, but even it saves one, that would be an improvement.	GUI
Brackettville Section/Del Rio Area	Low water crossings need to be updated. Many of the old metal pipes are failing and blocked with debris.	Log Jams
Junction	Flood Sensors Active Warning Lights.	Warning Lights
Lampasas Co. Maint./ Brownwood	Maybe have solar-powered flashing beacons on the fold-down ROAD FLOOD AHEAD signs that maintenance sections could monitor and activate during events, or small permanent digital message boards that would activate during events.	Solar-Powered Beacons
Texarkana	Flood sensors with solar panels seem to work well. So far, we have tried it at one location only.	Solar-Powered Beacons
Greenville	If there were a better way to keep drivers from getting across our barricades, it would help out tremendously.	Barricades
Hondo	We should get an electronic inventory and incorporate improvements in PS&E projects. Need more sensors as well.	Electronic Inventory

Only two area offices provided additional information (see Table 3-9). The Gainesville and Austin area offices responded that drivers continue to ignore warning signs. The Gainesville area office is focusing more on driver inattention. The Austin District described the geography of the area that leads to frequent flooding occurrences in the region.

Table 3-9. Individual Responses for Requests for Additional Information.

TxDOT Area Office	Response
Gainesville	Hard to drive for people who continue to ignore the warning signs and lights. TxDOT goes above and beyond in most cases, but people still don't pay attention.
Austin District Operations	The Texas Hill Country is a region known for its rocky hills, springs, and canyons. Due to this geography, roadway flooding is a natural hazard and a frequent occurrence in the area.

3.2.8 Analysis of Written Responses

The format of the survey offered respondents the opportunity to provide written text in response to the questions. This approach helped the researchers identify specific problems and solutions offered by the area offices. However, extracting knowledge from these unstructured texts was difficult. One way of analyzing such text is to perform text mining. Text mining is an applied method that originated from more general scientific research known as data mining or knowledge discovery. Knowledge discovery is the non-trivial process of identifying valid, useful, and easy-to-interpret patterns in data. Knowledge discovery in text (KDT), or text mining, is considered a multistage process that comprises all activities from document collection to knowledge extraction. KDT utilizes approaches like data mining, information retrieval, supervised and unsupervised machine learning, and natural language processing (NLP). Extraction of quick and useful information from data resources through pattern recognition helps identify contributing factors in associated tasks. Text mining algorithms can handle massive collections of unstructured textual data.

In information retrieval approaches, keywords are assumed to represent compact information in documents. Keyword extraction uses an NLP method to identify words or term tags that are combined with supervised or unsupervised machine learning algorithms. Word clouds show the frequency distribution of the most frequent words in the document. For example, from all responses to Question 5, the researchers developed a word cloud (minimum word frequency of 10), shown in the top left of Figure 3-9. The size and color of each word indicate several different thresholds. In general, the larger the text, the more frequent the word in the document. Figure 3-9 and Figure 3-10 show the word cloud developed for each question.

Question 5 (Countermeasures).

Question 7 (Alternatives).

Question 8 (Countermeasures).

Question 9 (Success/Failure).

Figure 3-9. Word Clouds Developed from Written Responses of Questions 5, 7, 8, and 9.

Question 10 (Consideration).

Question 11 (Prioritization).

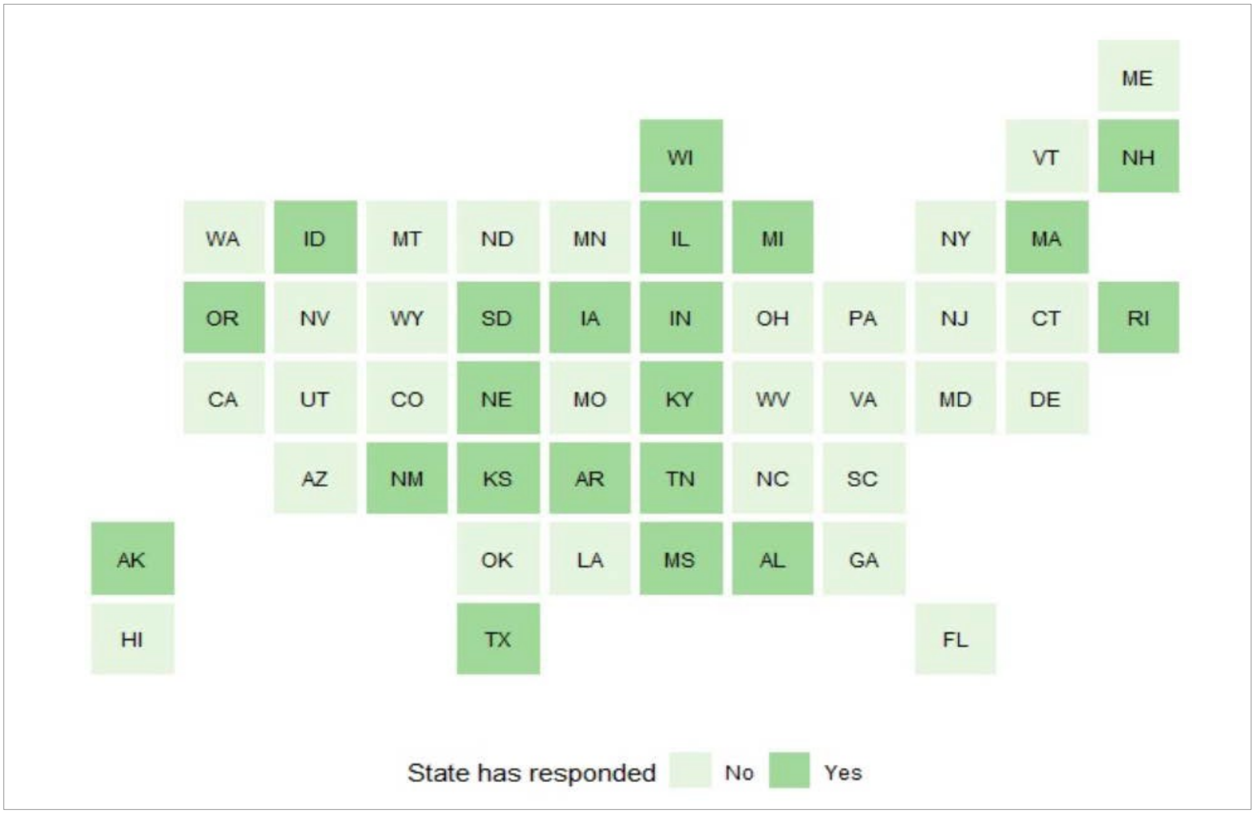
Question 12 (Additional).

Question 13 (General Comments).

Figure 3-10. Word Clouds Developed from Written Responses of Questions 10–13.

3.3 OTHER STATE DOTS

The researchers also surveyed other state DOT agency offices concerning their current LWC practices. From a pool of DOT agency office personnel, 24 participants completed the survey. This section highlights the key findings of the survey of other state DOTs. Figure 3-11 illustrates the U.S. map showing the responses received from each state.



Source: Texas A&M Transportation Institute

Figure 3-11. Survey Responses by States.

From the breakdown of responses shown in Table 3-10, the researchers found that around 92 percent of respondents indicated that their agency offices do not have LWC inventories. In response to Questions 4 and 5, 12 percent of respondents indicated that their agency offices have developed LWC design and countermeasure implementation protocols. The responses regarding problem diagnosis and alternatives suggest that none of the agency offices (100 percent) have developed any specific criteria or methods. The researchers found similar negative responses regarding consideration of location/scenario characteristics for LWC implementation.

Table 3-10. Other State DOT Response Rates to Survey Questions.

Questions	Number of "Yes" Responses	Number of "No" Responses	Did Not Respond
Does your agency have an inventory for low water crossings?	2	22	0
Has your agency developed low water crossing design and countermeasure implementation protocols (i.e., barricades, flood sensors, passive signs, and active warning devices)?	3	21	0
Has your agency developed any criteria/methods for diagnosing problems and developing alternatives concerning low water crossings?	0	24	0
Please list the different low water crossing countermeasures your agency has implemented (i.e., barricades, flood sensors, passive signs, active warning devices). For each of the listed countermeasures, please provide as much feedback as possible about their functionality, installation, maintenance, operation, etc. You can also upload files of the developed criteria as an attachment if preferred.	18	6	0
Based on your experience, how would you categorize the success (or failure) of both passive and active devices utilized by your agency to improve visibility and alert motorists of flooding events at low water crossings?	13	11	0
When selecting different low water crossing countermeasures for implementation, does your agency consider location/scenario characteristics? (For example, you implement countermeasure Type A for scenarios that are Type 1 and Type 2.) If so, would you be able to share the main reasoning for your choices?	3	19	2
How does your agency prioritize the characteristics of locations where future device deployment is most needed?	11	13	0
Are there any other relevant issues or ideas concerning low water crossings that you would like to share/discuss (i.e., design considerations, operational challenges, need for connected vehicle technologies, and smartphone apps for flood hazard warning)? These can be issues you are already facing or suggestions that you identify as possible solutions for low water crossing locations.	15	9	0
Are there any other comments you would like to share with the Project Team? If so, please feel free to include your comment(s) in the comment box below.	16	8	0

Figure 3-12 shows the percentage distribution of responses for Questions 2, 4, 6, and 10 regarding inventory data of LWCs, countermeasures, design alternatives, and major considerations.

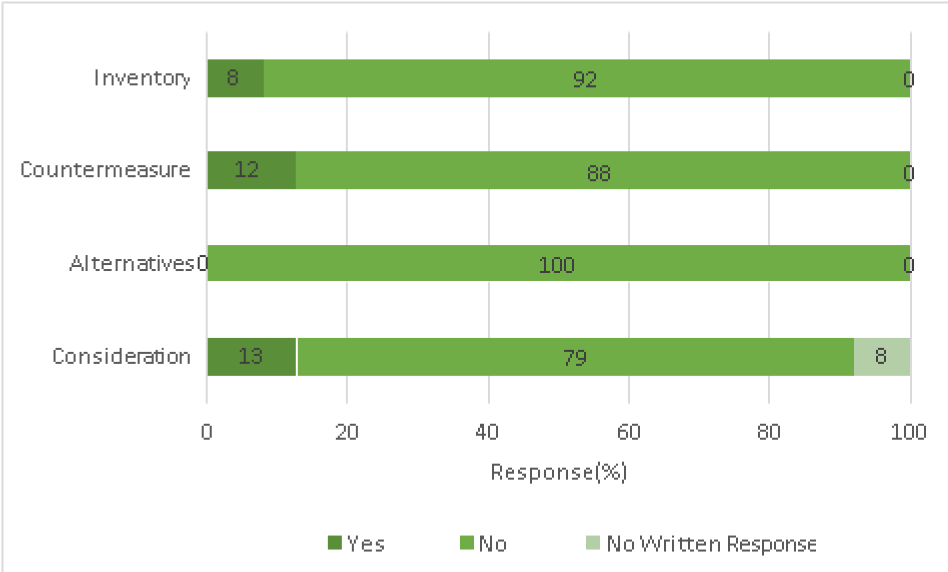


Figure 3-12. Other State DOT Survey Responses for Questions 2, 4, 6, and 10.

3.3.1 Inventory of LWCs and Flood-Prone Roadways

The researchers also asked the other state DOTs whether agency offices have existing inventories of their LWCs. Those who responded yes to this question either uploaded a document on relevant field studies or shared further inventory data details.

Regarding the implementation protocols and countermeasures, the respondents provided a range of responses regarding their protocol options. Figure 3-13 shows different protocols that other DOTs use at their LWC locations. The review found that barricades and signings are the most commonly used protocols. Table 3-11 lists individual responses received from different districts.

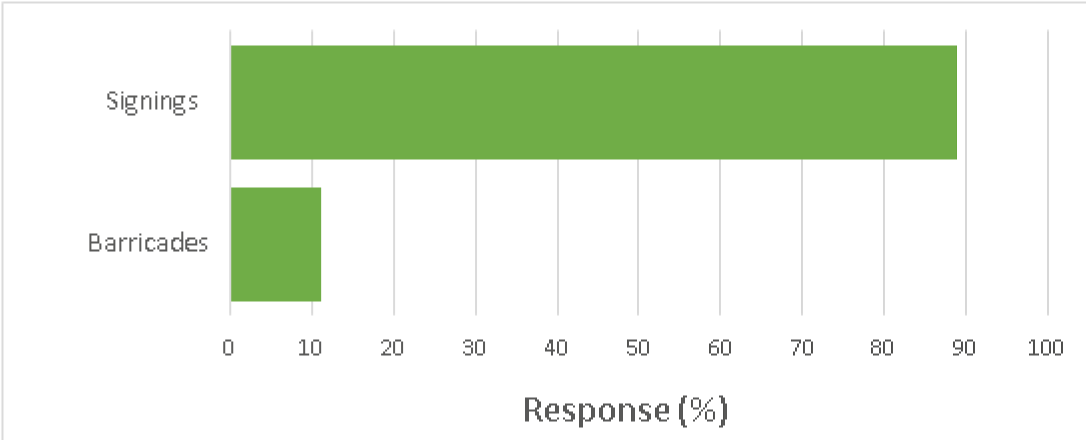


Figure 3-13. Types of Protocol and Countermeasures Identified by Other State DOT Survey Respondents.

Table 3-11. Individual Responses from Other State DOTs for Protocol and Countermeasures Survey Question.

State	Response	Solution
AK, AL, AR, IA, ID, IL, IN, KS, MA, MS, NH, NM, OR, RI, SD, TN, WI	No Response	N/A
KY	We have identified signing options (both permanent and temporary). See the following link: https://transportation.ky.gov/Organizational-Resources/Policy%20Manuals%20Library/Traffic%20Operations.pdf. See Section TO-403-2 and Exhibit 24.	Signings
MI	When required, barricades are placed.	Barricades
NE	We don't have any on our state highway system but show a "low water crossing ahead" sign in our MUTCD Supplement.	Signings

3.3.2 LWC Management Alternatives

As shown in Table 3-12, none of the representatives from the other state DOTs responded to the question regarding LWC management alternatives.

Table 3-12. Types of LWC Management Alternatives Identified by Other State DOT Survey Respondents.

State	Response	Solution
AK, AL, AR, ID, IA, IL, IN, KS, KY, MA, MI, MS, NE, NH, NM, OR, RI, SD, TN, WI	No Response	N/A

3.3.3 Factors Considered in Developing and Implementing LWC Treatment Strategies

The researchers determined it was important to understand the location or scenario characteristics that are considered for specific countermeasures or design alternatives. The researchers asked the other state DOTs to list the factors they considered necessary to develop and implement LWC strategies. Table 3-13 lists individual responses from different area offices to this question.

Table 3-13. Individual Responses from Other State DOTs for LWC Considerations Survey Question.

State	Response	Comment
AK, AL, AR, IA, ID, MA, MI, MS, NE, NH, NM, OR, RI, TN, WI	No Response	N/A
AR	Yes	If a low water crossing were experiencing problems to the level that I would become involved, I would consider a permanent final design that meets AASHTO requirements, in addition to possible design exceptions. I would also meet NFIP regulations if applicable. I have only had one washout issue that I have developed a design for at a location that would be considered a low water crossing.
IL	Yes	Local Public Agencies construct these low water crossings without much involvement (if any) from the IL DOT.
IN	Yes	There are not many locations where there is an issue, and we currently have taken a reactive approach.
KS	No	N/A
KY	No	We have no specific criteria. Left up to engineering judgment.
SD	No	I do not know of any low water crossing countermeasures we routinely use.
TN	Yes	All countermeasures are custom designed for each location.

3.3.4 Traffic Control Countermeasures at Flooded LWCs

Researchers asked for additional information regarding the types of traffic control countermeasures other state DOTs use at LWCs when flooded. Figure 3-14 illustrates the percentage distributions of the key countermeasures identified. Barricades and signings are the most used countermeasures. Table 3-14 lists individual responses from other state DOTs to this question. Respondents from several states (Arkansas, Iowa, Rhode Island, and Tennessee) indicated that they do not have LWCs in their regions.

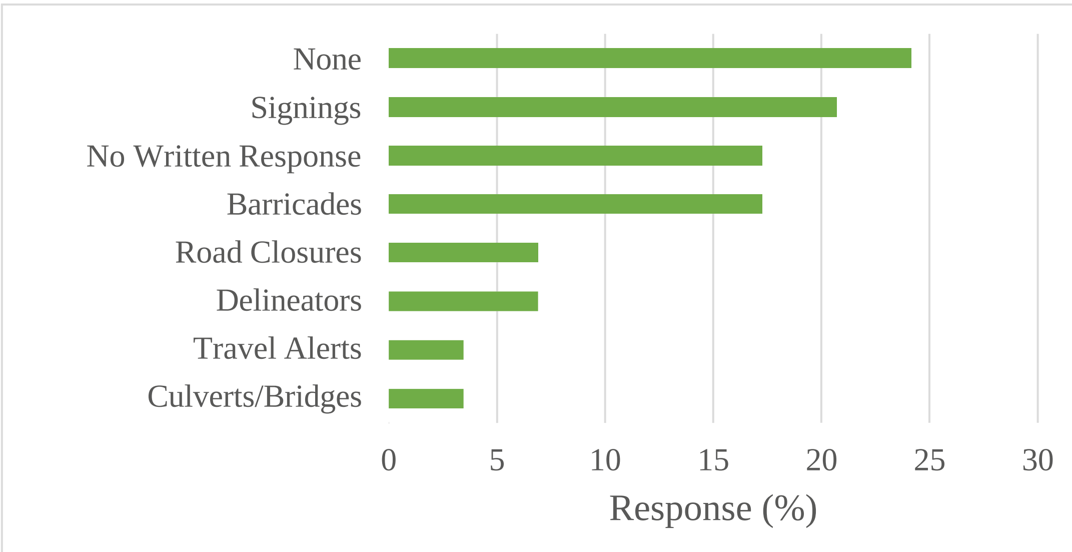


Figure 3-14. Types of Traffic Control Devices Deployed by Other State DOTs at Flooded LWCs.

Table 3-14. Individual Responses from Other State DOTs for Traffic Control Countermeasures Survey Question.

State	Response	Solution
AK	I am not aware of any.	None
AK	I am not aware that there are any low water crossings or potential low water crossings in our region.	None
AL	We have only used some warning signs at a few locations where we occasionally have water topping a roadway during heavy rainstorms. There is no active monitoring or sensing in place or planned at this time.	Signings
AR	Barricades and passive signs. We do have Idrivearkansas.com that provides road closure information that includes closures for high water.	Barricades, Signings
AR, ID, IL, MA, SD, WI	No Response	N/A
IA	We do not have any low water crossings on the state highway system in Iowa.	None
IN	We have no policies in place. In some cases, we have permanent passive signs, and in other cases, we place signs when flooding of the roadway develops. We are working with a vendor to test an automated high-water sign.	Signings, Barricades
KS	I do not know whether KDOT has an inventory of Low Water Crossings. It would be my opinion that there are no low water crossings on the state system. If there are, I would expect that there is a listing of these crossings. I have lived in the state for many years, and I know that there are low water crossings all over the state of Kansas on local roads. These roads are frequently closed due to the potential of flooding.	Road Closures
KY	Optional use of permanent ROAD MAY FLOOD signs where roads frequently flood. We use this treatment typically where roadways flood often. Optional, we use temporary WATER OVER ROADWAY signs when roads flood. This treatment is typically installed by maintenance crews when water covers the roadway. At District's discretion, crews may use barricades when a road needs to be closed due to high water. I am not aware of any use of flood sensors or active warning devices. We had fielded one request to consider such technology after a fatality on one of our roadways, but we identified funds to raise the roadway.	Signings, Barricades

State	Response	Solution
MI	Traffic control has consisted primarily of road closures and detours. Utilizing Law enforcement, static DMS signs, portable CMS signs, and temporary roadside signs. During the 2011 MS River flood, we installed snap-back delineators through the US61/MS3 interchange to guide construction traffic for levee work.	Road Closures, Signings, Delineators
MI	Barricades—We would typically place barricades and post a detour when water is over the road, assuming it is an extended duration.	Barricades
MS	On different occasions, we've used: Barricades, static signs, changeable message signs, travel alerts through MDOT's traffic website & mobile app (MDOTTraffic). On one occasion, during a flood event, where several state highways were underwater, we deployed snap-back delineators along the shoulder on some consistent spacing—say 100 feet. First responders use these to gauge the depth of the water over the road, so they might know whether their trucks could pass through or not.	Barricades, Signings, Travel Alerts, Delineators
NH	Locations are addressed on a case by case basis. While there are a handful of repeat offenders around the state, they are not generally associated with rapidly moving water and are addressed by placing barricades across the road during high water events.	Barricades
NM	Nothing, so far, has been developed. As a rule, we try to eliminate our low water crossings.	None
OR	From the DOT's perspective here in Oregon, we do not use low-water crossings. All state-owned crossings have culverts or bridges. Our general policy is that all culverts or bridges should have a minimum of 3' of clearance between the design storm and the bridge/culvert opening's low chord. For areas where raising the roadway to give this 3' of clearance would cause access issues in the community, we have a waiver process to use only 1' of clearance. This waiver is only used in areas, typically along the coast, where raising the road above flood levels would cause access issues without alleviating the flooding in the community.	Culverts, Bridges
RI	We do not have low water crossings.	None
TN	We have almost no low water crossings in-state inventory as our standards specify a minimum 10-year flood design on state routes. We do not have standard criteria, and countermeasures are deployed on a case by case basis when Operations staff determine it to be necessary. A number are owned by local governments and inspected by state crews.	None

3.3.5 Degree of Success (or Failure) of Passive and Active LWC Devices

The researchers asked the other state DOTs to assess the implemented countermeasures' effectiveness at LWC locations based on their experiences. The success rate is higher than the failure rate (see Figure 3-15). Table 3-15 lists individual responses from different state DOTs. Arkansas indicated that it has few LWC locations. New Hampshire mentioned that static signs are not very effective at warning drivers of occasional hazards.

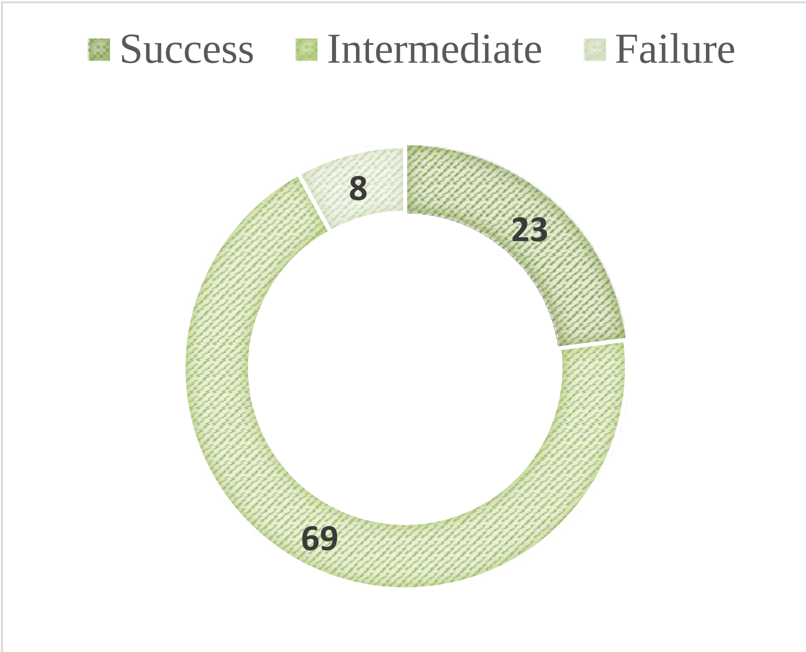


Figure 3-15. Other State DOT Responses for Degree of Success of Passive and Active LWC Devices Question.

3.3.6 Prioritization Criteria

The researchers asked about the criteria that other state DOTs used to prioritize locations where future devices are most needed. Most of the respondents could not identify an area of concern. However, some respondents recommended that local operations engineers address the problem and prioritize accordingly. Table 3-16 lists individual responses from different agency offices.

Respondents from Indiana indicated that they do not inventory LWC locations. Massachusetts indicated that prioritization is usually done based on the frequency and duration of overtopping events and the associated road closure.

Table 3-15. Individual Responses from Other State DOTs for Degree of Success Survey Question.

State	Response	Comment
AK, AL, AR, IA, IL, MA, RI, WI	No Response	N/A
AR	Intermediate	The Department has very few low water crossings on the state highway system. The counties would have more experience with and maintain their low water crossings on the county road system.
ID	Intermediate	Idaho's climate and watersheds are somewhat different than those in the southwestern states. We don't have the same issues with low water crossings. You'll probably receive better information from states like Arizona and New Mexico.
IN	Intermediate	Limited success, the traveling public doesn't always use caution when warned about high water across roadways.
KS	Intermediate	I have no experience in this area of engineering.
KY	Intermediate	This is not something that our Cabinet has investigated thoroughly. However, we are not aware of any significant issues, nor has anybody requested additional treatments beyond signing and maintenance crews' responses when there is an issue.
MI	Success	Very successful.
MI	Success	Passive Barricades do serve a purpose in a short duration.
MS	Success	We don't have much experience with active warning devices for low water crossings. I'd categorize our efforts as largely successful concerning the use of passive devices.
NE	Intermediate	These are all on our local system and not under our jurisdiction.
NH	Failure	While we do not have experience in this category, in general, passive (assumed to refer to static signing that does not reflect real-time conditions) is not very effective at warning drivers of occasional hazards.
NM, OR, TN	N/A	N/A
SD	Intermediate	I do not know of any low water crossing countermeasures that we utilize.
TN	Intermediate	I am not aware of many state routes susceptible to regular flooding.

Table 3-16. Individual Responses from Other State DOTs for Prioritization Criteria Survey Question.

State	Response	Solution
AK, AL, IA, IL, MA, MI, NM, OR, RI, TN, WI	No Response	N/A
AR	Deployments consist of replacement usually, and it's up to the District Engineers to determine when problems get addressed.	District Engineers
ID	No typical method.	N/A
IN	We do not have a database of locations. We would base future device deployment on a discussion with maintenance personnel on sites where they periodically have to place high water signage.	District Engineers
KS	No Experience.	N/A
KY	Local Districts decide based on their knowledge of locations.	Personal Knowledge
MI	In my opinion, we have always been reactionary to highway flooding and treated each event as necessary with the resources at hand. Each location and high-water event has been different.	Personal Knowledge
MS	We have not conducted a prioritization. I would imagine we would prioritize locations based on the frequency of overtopping events and road closure duration per event.	Overtopping, Road Closure
NE	See the criteria in the previous attachment.	N/A
NH	Not applicable.	N/A
SD	I do not know of any low water crossing countermeasures that we have utilized.	None
TN	Recommendations by local operations staff and local governments.	District Engineers

Agency officials also responded to Question 12, which asks for relevant issues and ideas concerning LWCs. Most answered that they do not have any relevant issues or ideas relating to LWCs. Table 3-17 lists individual responses from different agency offices for Question 12. Respondents from Alabama and Arkansas indicated that they have very few LWCs under their jurisdictions.

Table 3-17. Individual Responses from Other State DOTs for Requests for Other Relevant Issues and Ideas.

State	Response	Solution
AK, IA, ID, KS, KY, MA, MI, MS, NE, NH, TN	No.	N/A
AL	We have so very few of these locations that it is not something on which we focus.	N/A
AR	There are very few crossings on the state highway system, and we rarely need to attend to them. I do not have any suggestions without knowing what problems other states are experiencing.	N/A
AR, IL, MI, NM, OR, RI, WI	No Response	N/A
IN	Not currently.	N/A
SD	I do not know of any low water crossing countermeasures that we have utilized.	N/A
TN	No. Local governments in Tennessee probably have more experience with low water crossings.	N/A

The researchers asked each survey respondent about further comments they wanted to share, if any. Most respondents did not respond to this question, but the researchers did receive responses from six agency offices. Table 3-18 lists individual responses from the different agency offices. One respondent from Tennessee recommended not using LWCs except in very low traffic locations.

Table 3-18. Individual Responses from Other State DOTs for Requests for Additional Information.

State	Response	Solution
AK, IA, ID, KY, MA, MS, NE, TN	No.	N/A
AK, AR, IN, MI, NM, OR, RI, WI	No Response	N/A
AL	Not at this time.	N/A
AR	Any guidance or recommendations on the topic will be appreciated as we work with the counties with most of the state's low water crossings.	Further Guidance
IL	The Illinois Department of Transportation worked with the Illinois Center for Transportation on ICT PROJECT R27-148 "Development of Low-Water Crossing Design Guidelines for Very Low ADT Routes in Illinois," which was published in November 2016 and may be found at https://apps.ict.illinois.edu/projects/getfile.asp?id=5066.	Design Guidelines
KS	Thank you for including me in the survey. It would have been nice to have an option of no experience in this area before starting the survey. Best wishes on your research.	N/A
MI	I am not aware of any dedicated low water crossings on the state highway system that flood regularly or require routine TCD deployment.	N/A
NH	Good luck.	N/A
SD	I do not know of any low water crossing countermeasures that we have utilized.	N/A
TN	I realize it isn't useful to your research, but I recommend that low water crossings should not be used except in extremely low traffic situations. In addition to safety issues to the traveling public, low water crossings tend to exacerbate upstream flooding.	Design Considerations

Based on the survey findings, the TTI researchers contacted two states (Indiana and Illinois) for further information. A brief phone conversation with the respondent from Illinois indicated that local agencies maintain the LWCs instead of the state DOT and led the researchers to a project report developed by the Illinois Center for Transportation, *Development of Low-Water Crossing Design Guidelines for Very Low ADT Routes in Illinois* (*7*).

3.4 SUMMARY OF SURVEY RESULTS

The general findings of the survey of TxDOT area offices and other state DOTs are summarized below.

For TxDOT area offices:

- The survey results show a comprehensive picture of Texas area offices' LWC inventories and related practices.
- Around 88 percent of respondents indicated that the area offices do not have LWC inventories.
- Many area offices provide information to HCRS.
- Around 44 percent of respondents indicated that the area offices have developed LWC design and countermeasure implementation protocols.
- Most of the area offices (around 64 percent) have not developed any specific criteria or methods.
- The researchers found no specific recommendations for the consideration of high-priority locations for LWC countermeasure implementation.

For the other state DOTs:

- The survey results show a comprehensive picture of the LWC inventories and related practices by agency offices in the United States.
- Around 92 percent of respondents indicated that the area offices do not have LWC inventories.
- Around 12 percent of respondents indicated that the agency offices have developed LWC design and countermeasure implementation protocols.
- Several states have very few to almost no LWCs on their state-maintained roadways.
- None of the agency offices developed any specific criteria or methods.
- The researchers found no specific recommendations for the consideration of high-priority locations for LWC countermeasure implementation.
- Barricades and static signs are the most common countermeasures.

Chapter 4. CROSS-REFERENCE DATABASE

4.1 INTRODUCTION

The researchers used the following data sources to develop the cross-reference database product (P3) for this study:

- Five years (2013–2017) of CRIS data.
- 2017 Roadway Highway Inventory Network Offload (RHiNO).
- LWC Database from TNRIS.
- LWC Database from Highway Condition Reporting System (HCRS).

4.2 EXISTING DATABASES

4.2.1 Crash Records Information System

Crash data were collected and archived uniquely for each state. In Texas, as an example, law enforcement is responsible for documenting and reporting crash information. TxDOT is responsible for assembling and maintaining this information in a crash database known as CRIS. CRIS contains multiple tables that are linked by a common crash designation identification number. These tables summarize information related to the crash, each vehicle (or unit), and each person involved in the crash. Figure 4-1 is a schematic format of this configuration.

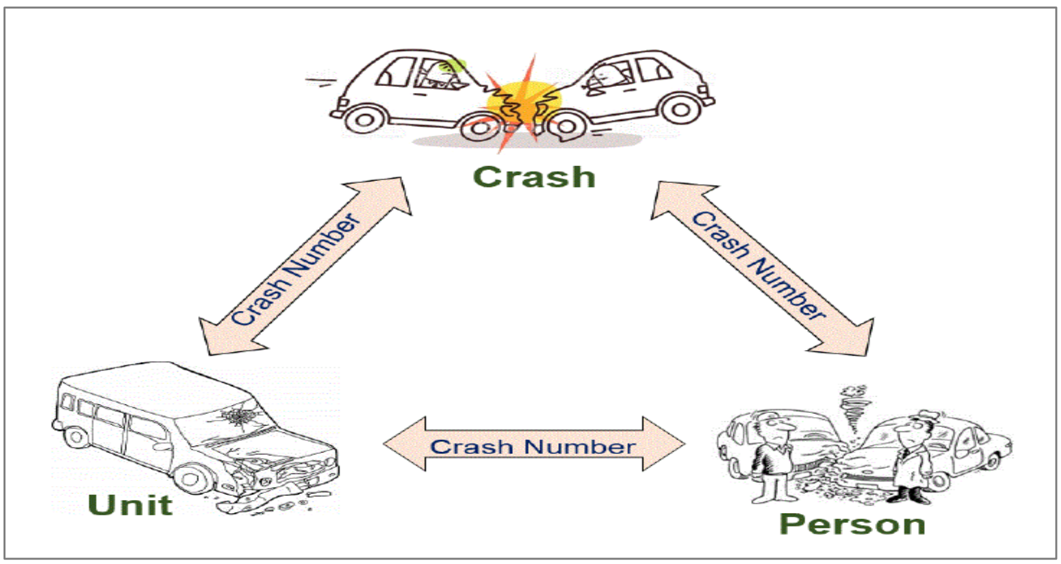


Figure 4-1. CRIS Data Elements.

4.2.2 Roadway Highway Inventory Network Offload

In addition to the CRIS database, TxDOT also maintains a database that includes various roadway characteristics. This database, known as RHiNO, supplements information from the crash database (see Figure 4-2).

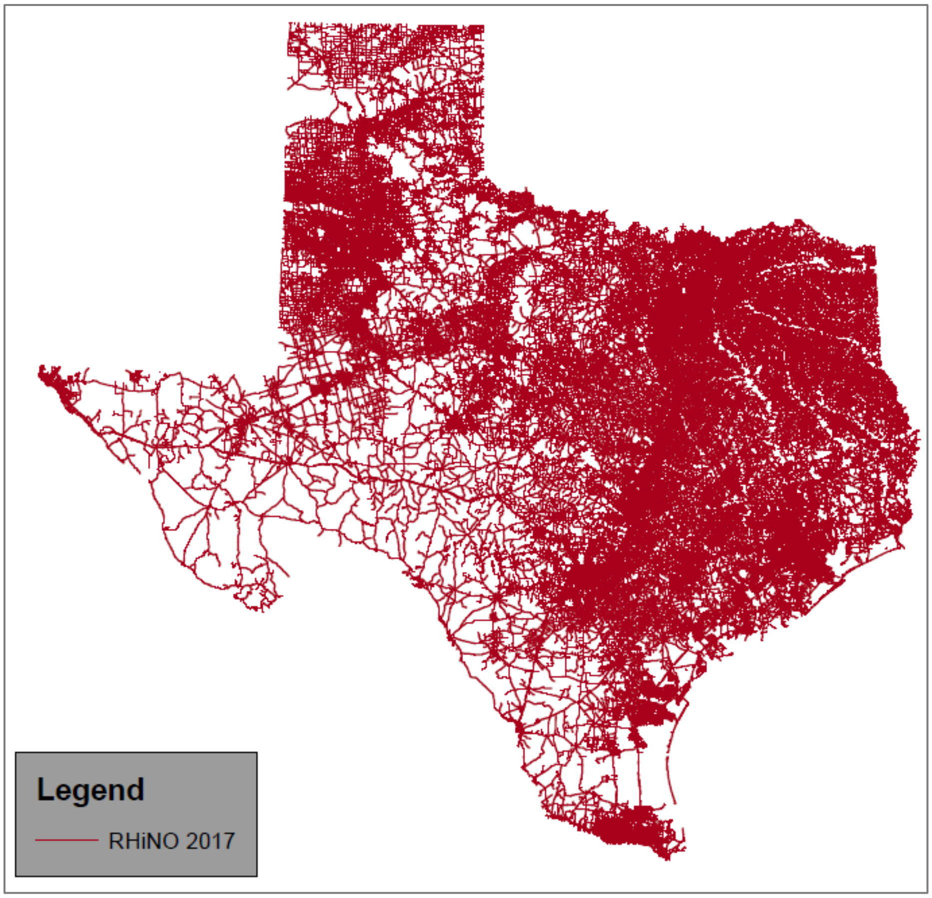


Figure 4-2. RHiNO Network (2017).

4.2.3 Texas Natural Resources Information System LWC Database

TNRIS maintains a location database of LWCs in Texas (as shown in Figure 4-3). The purpose of this database is to locate all existing LWC locations. This database provides the location of 8,339 LWCs in Texas.

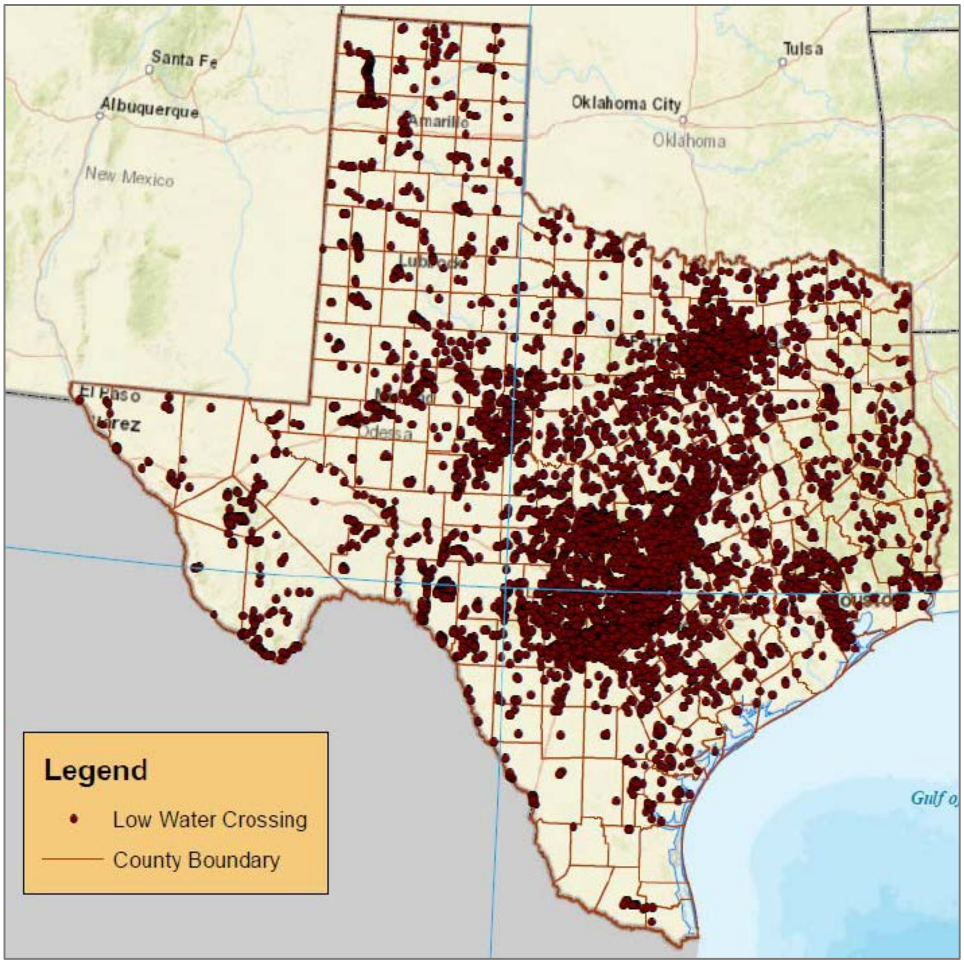


Figure 4-3. TNRIS LWC Locations.

4.2.4 Highway Condition Reporting System LWC Database

HCRS maintains a spatiotemporal database of all roadway events in Texas (see Figure 4-4). This database contains 263,755 events. Around 2.62 percent of these events are LWC related.

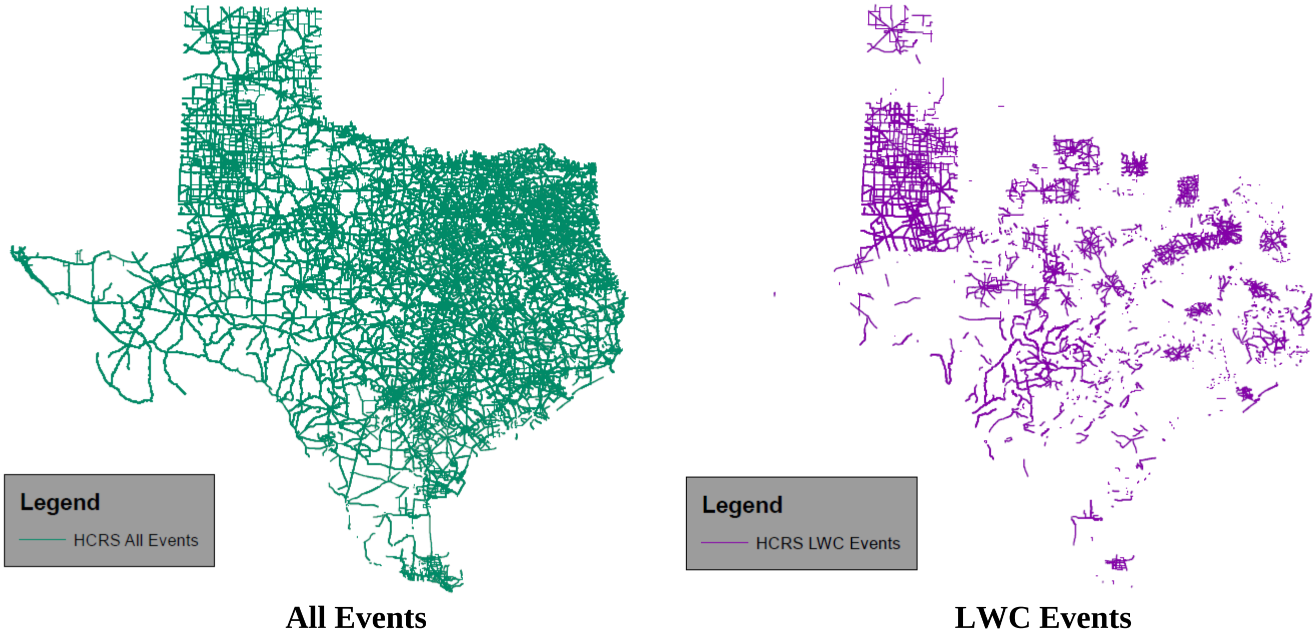


Figure 4-4. HCRS Events.

4.3 DATA INTEGRATION

4.3.1 Dataset 1: TNRIS LWC Crash Database

The researchers divided the data integration work into three processes:

- Process 1: Conflate the TNRIS LWC locations on RHiNO segments.
- Process 2: Assign the number of LWC locations on RHiNO segments.
- Process 3: Develop a shapefile of CRIS (2013–2017) data and assign crashes to nearest RHiNo segments.

Figure 4-5 shows the steps taken in each process, as also described below:

- Process 1: Use the “Near” function (threshold = 50 ft) to assign the TNRIS LWC locations to the nearest RHiNO segments (ArcGIS).
- Process 2: Create a shapefile of RHiNO with the number of LWC locations (see Figure 4-5) (ArcGIS).
- Process 3: Merge five years (2013–2017) of crash data. Create a shapefile of a crash dataset with available latitude and longitude (ArcGIS). Use the “Near” function (threshold = 25 ft) to assign the crashes to the nearest RHiNO segments (ArcGIS).

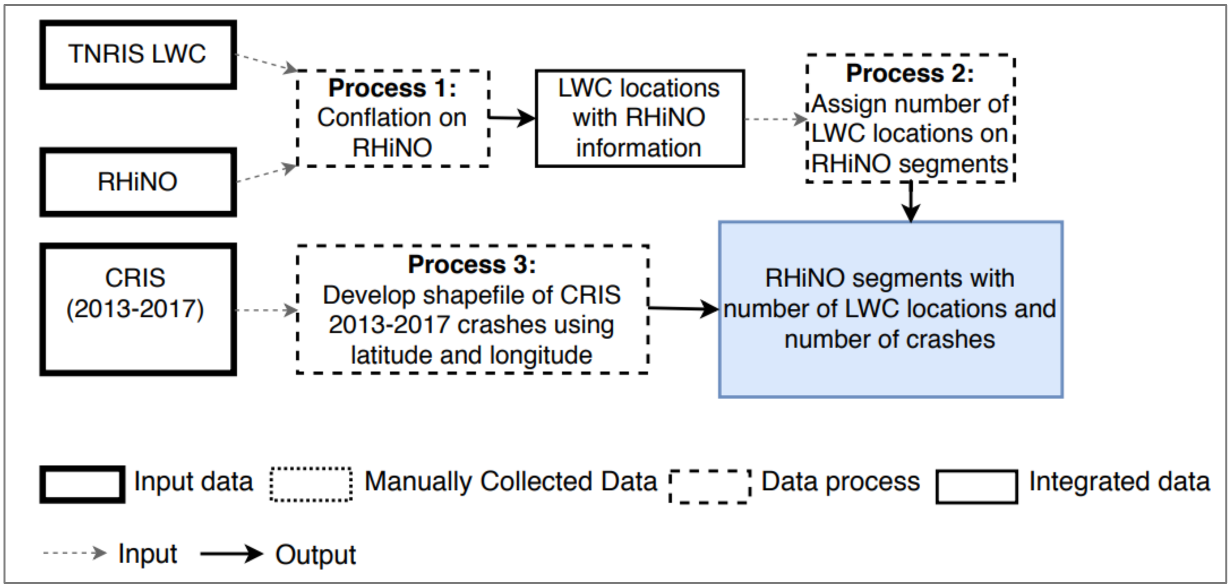


Figure 4-5. Flowchart of Data Integration Work.

4.3.2 Dataset 2: HCRS LWC Crash Database

The researchers divided the data integration work into three processes:

- Process 1: Select LWC events from the HCRS event database.
- Process 2: Assign crashes on HCRS LWC event segments.
- Process 3: Conduct temporal matching to match LWC events and crashes.

Figure 4-6 shows the steps taken in each process, as described below:

- Process 1: Prepare a subset of LWC events from HCRS events based on the text provided in an event description (R).
- Process 2: Merge five years (2013–2017) of crash data (R). Create a shapefile of the crash dataset with available latitude and longitude (ArcGIS). Use the “Near” function (threshold = 25 ft) to assign the crashes to the nearest HCRS LWC segments (ArcGIS).
- Process 3: Conduct temporal matching between HCRS event and crash event (R). Create a shapefile of the final dataset (ArcGIS).

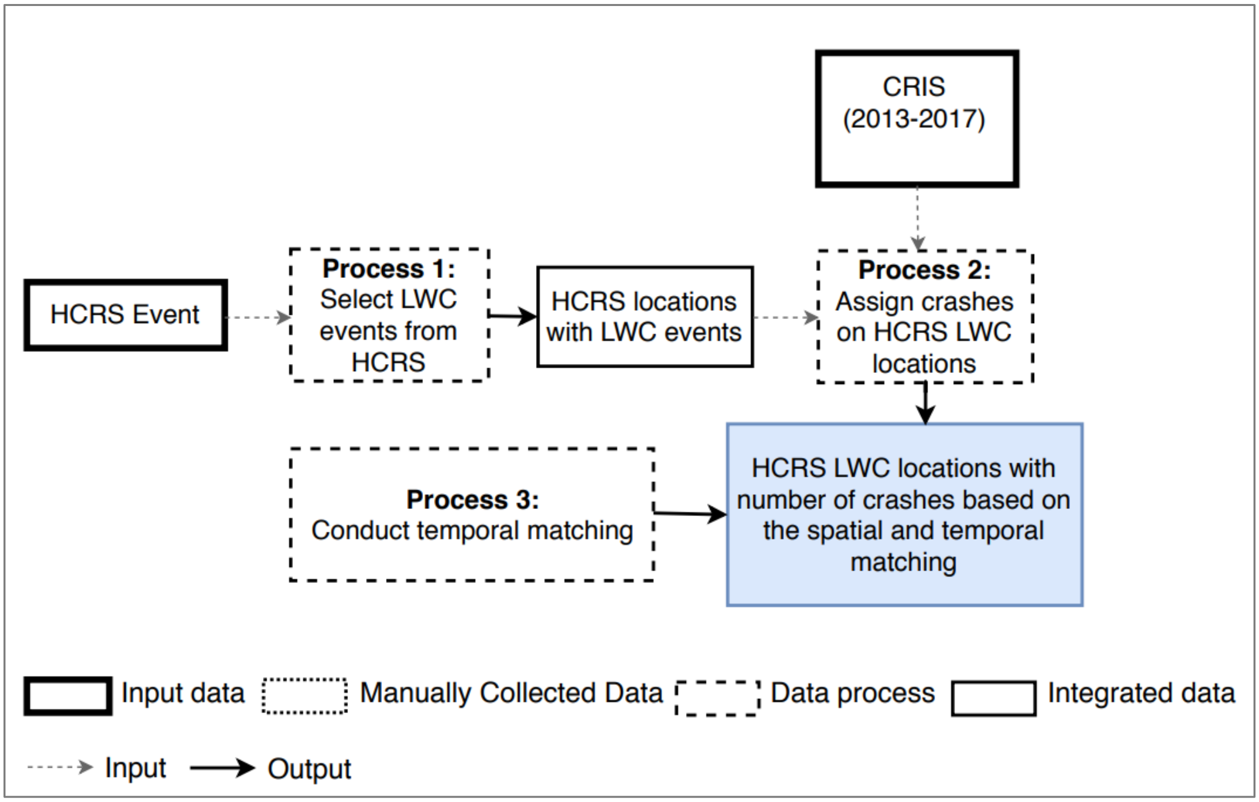


Figure 4-6. Data Preparation Flowchart for Dataset 2.

4.3.3 Dataset 3: CRIS Data with "Standing Water" as Surface Condition

The researchers developed a third dataset as a supplementary dataset that provides information regarding crashes associated with "standing water" as the surface condition. The researchers used the following steps to create this dataset:

- Merge five years (2013–2017) of crash data (R).
- Use filter "Surface Condition = Standing Water" to subset dataset with "standing water" as the surface condition (R).

4.4 EXPLORATORY DATA ANALYSIS

4.4.1 Dataset 1: TNRIS LWC Crash Database

Dataset 1 contained 70,616 crashes on the TNRIS LWC segments. Figure 4-7 shows the monthly distributions of total crashes on these segments. Dataset 1 indicated that these segments experienced a higher number of crashes during the rainy seasons. Figure 4-8 shows monthly precipitation trends (using the 1981–2010 National Oceanic and Atmospheric Association climate normal dataset) in Texas, which justifies the high precipitation during March to May and October.

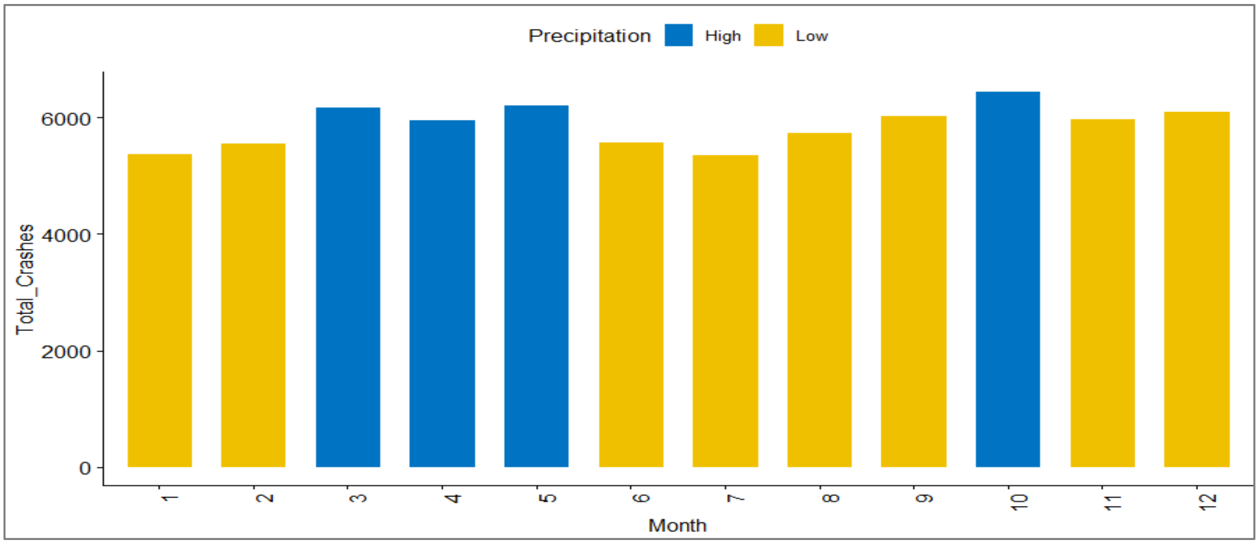


Figure 4-7. Traffic Crashes per Month on TNRIS LWC Segments (2013–2017).

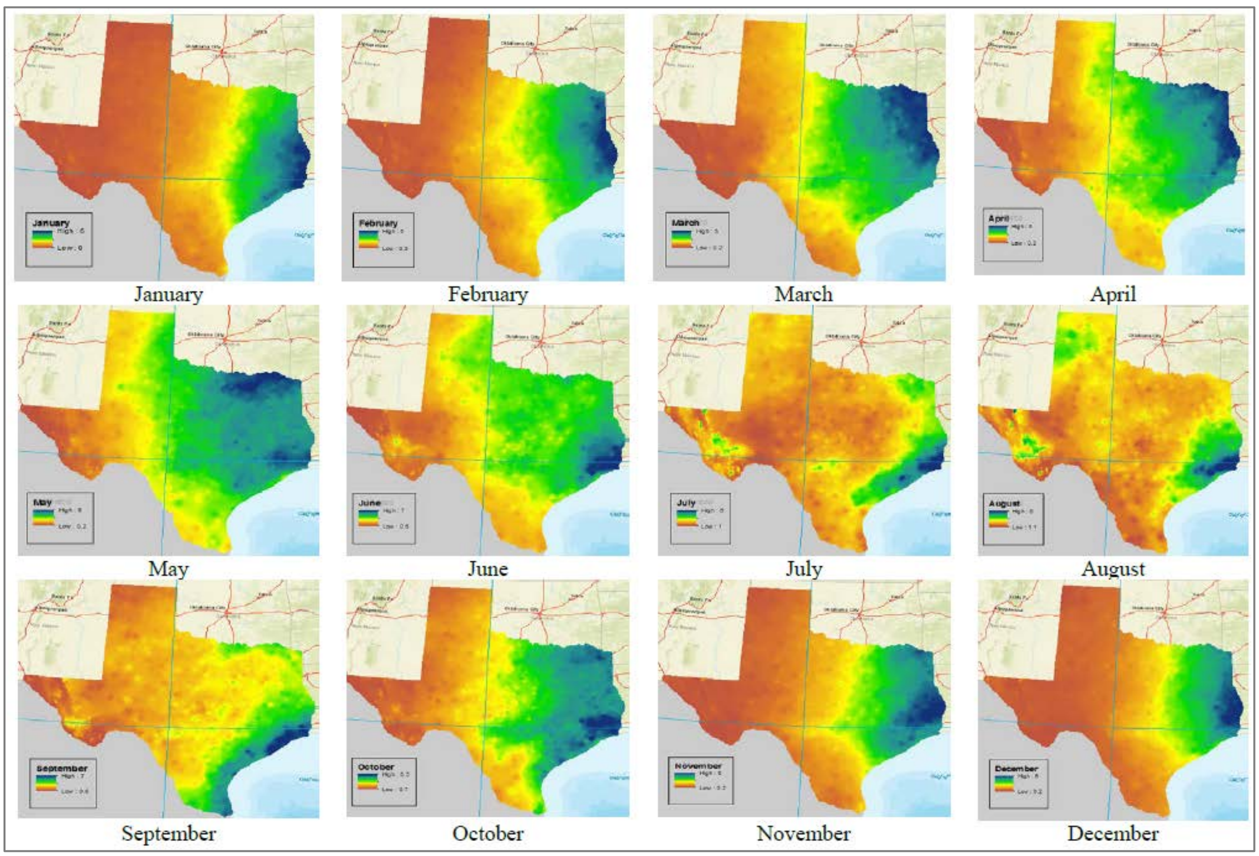


Figure 4-8. Average Monthly Precipitation in Texas.

Table 4-1 shows the top 10 counties and roadways that had a high number of LWC segment crashes per year. Dallas County had the highest number of LWC segment crashes per year. FM 1730 had the highest number of LWC segment crashes per year among the roadway segments.

Table 4-1. Counties and Roadways with Highest Number of LWC Segment Crashes/Year.

County	LWC Segment Crashes/Year	Roadway	LWC Segment Crashes/Year
Dallas	3,359	FM1730	109
Tarrant	2,063	SS0303	108
Bexar	1,628	SL0354	104
Harris	808	SH0066	55
Bell	639	SH0191	48
Travis	612	IH0030	48
Denton	388	SH0352	48
Webb	380	BU0287P	47
Collin	333	SH0031	38
Hays	294	SH0010	38

Table 4-2 lists the severity types of the crashes that occurred on these LWC roadways. Around 0.5 percent of these crashes involved fatalities. Approximately 35 percent of these crashes involved an injury.

Table 4-2. Severity Types.

Year	Fatal (K)	Incapacitating (A)	Non-incapacitating (B)	Complaint (C)	Unknown Injury (O)
2013	65	372	1,681	2,414	7,876
2014	70	429	1,626	2,571	8,410
2015	74	424	1,724	2,740	9,508
2016	68	450	1,835	3,072	10,112
2017	69	489	1,812	2,791	9,934

The researchers conducted another preliminary exploration to investigate the roadway functional classes and their associations with LWC segment-related crashes (see Figure 4-9). Minor arterial roadways represented the highest number of crashes.

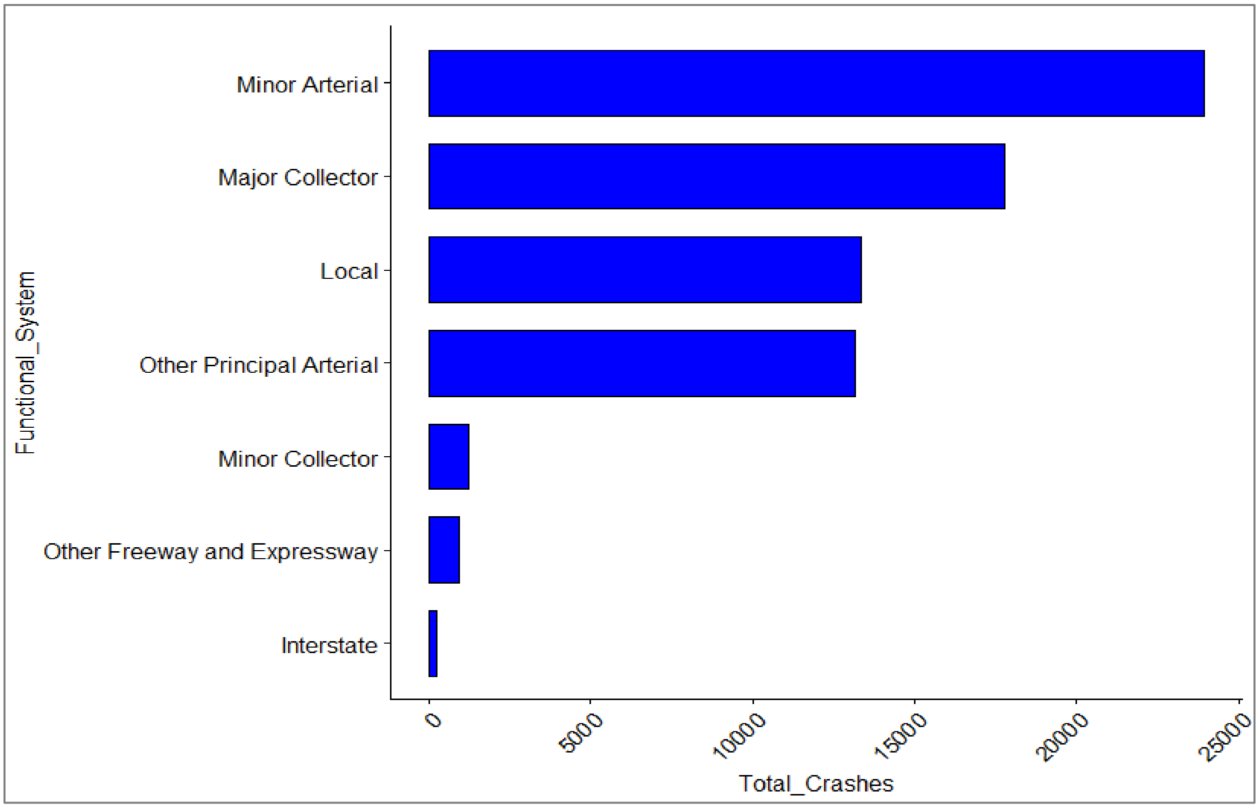


Figure 4-9. LWC Segment Crashes per Year by Roadway Functional Class.

The researchers determined that it was also essential to investigate how many of these crashes were on the on-system roadways. Table 4-3 shows that many of the crashes happened on the off-system roadways (county roads and city streets).

Table 4-3. Percentage of Crashes by RHiNO Record Types.

REC	Description	Percentage of Crashes
0	Grade Separated Connector On-System	0.02
1	On-System Main Lanes 2	17.33
2	On-System Right Frontage Road	0.95
3	On-System Left Frontage Road Off-System	1.08
5	County Road	45.48
6	Functionally Classified City Street	14.12
7	Local City Street	20.59
8	Non-TxDOT Toll Authority Road	0.11
9	Federal Road	0.32

4.4.2 Dataset 2: HCRS LWC Crash Database

The HCRS database contains flood-related events in a tabular format. The dataset has an event description column that provides narrative text on the event. The acquired dataset contains information on 6,935 events associated with LWCs. After performing spatiotemporal matching, the researchers found 144 crashes (around 2 percent of all LWC flood events). Figure 4-10 shows a word cloud comparing the crash event description narrative and no crash events. Some of the intuitive words in the crash narrative word cloud are as follows: frontage, closed, discourage, barricade, overnight, don't, and falling.

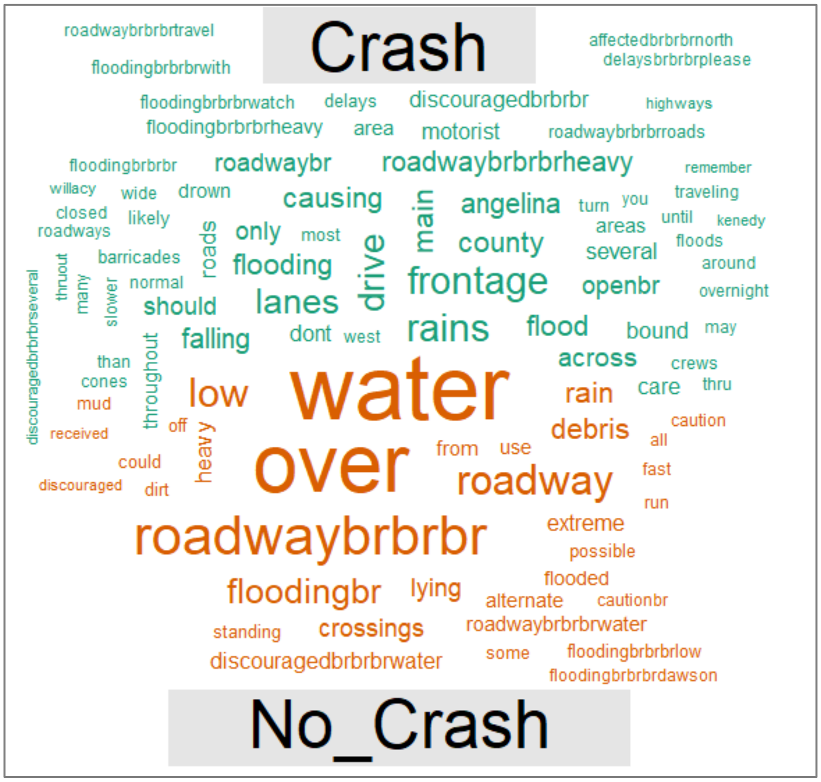


Figure 4-10. Comparison of Word Cloud.

4.4.3 Dataset 3: CRIS LWC Crash Data with "Standing Water" as Surface Condition

The researchers filtered for "standing water" in the CRIS database to create the third dataset. An average of 2,885 crashes occurred due to standing water on roadways in Texas from 2013 to 2017. Around 27 percent of these crashes involved a fatality or injury. Table 4-4 shows the heatmap of crashes by month from 2013–2017. The highest number of crashes occurred during April through June and in October.

Table 4-4. Heatmap of Crashes by Month from 2013–2017.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2013	249	90	88	186	192	149	201	103	336	335	144	119
2014	45	77	136	107	321	198	163	134	324	155	266	181
2015	266	97	365	438	823	405	103	123	178	625	471	278
2016	117	120	334	426	504	404	111	466	256	82	220	280
2017	302	178	233	224	154	313	197	408	145	125	78	278

Table 4-5 is a heatmap of crashes by month and weather conditions. May represents the wettest month, with the highest number of rain-involved crashes.

Table 4-5. Heatmap of Crashes by Month and Weather Conditions.

Month	Clear	Cloudy	Rain	Sleet/Snow	Other
Jan	88	79	797	7	8
Feb	50	51	452	7	2
Mar	71	121	951	7	6
Apr	93	142	1,129	12	5
May	132	211	1,631	6	14
Jun	100	155	1,211	1	2
Jul	84	57	625	1	8
Aug	85	128	1,019	0	2
Sep	86	122	1,025	1	5
Oct	81	82	1,152	2	5
Nov	64	99	1,005	5	6
Dec	68	95	960	10	3

4.5 CONCLUSIONS

This chapter presented the work performed in Task 3 of TxDOT Project 0-6992. The general findings are below:

- The exploratory data analysis identified high-priority roadway segments that require attention.
- Minor arterial and major collector roadways showed the highest number of LWC segment-related crashes.
- Every year, around 2,885 crashes occur on Texas roadways due to standing water. Approximately 27 percent of these crashes involve a fatality or injury.

Chapter 5. EVALUATION OF PAVEMENT MARKINGS AND MARKERS FOR LWCS

5.1 INTRODUCTION

Pavement markings are often considered when implementing low-cost countermeasures to improve safety for a variety of situations. LWCs may be a potential location where pavement markings and markers can be implemented as low-cost countermeasures to improve safety. These marking and marker treatments could serve to warn or guide drivers during high-water conditions, while also providing benefits during low-water situations. Depending on traffic volumes, some LWCs may have limited or no pavement markings. At other crossings where markings and markers are present, those treatments may not be adequately visible across a range of environmental conditions.

The objective of Task 5 was to evaluate the change in visibility of marking and marker treatments when submerged and not submerged in water. The contrast of the treatments to the surrounding road surface serves as a measure of the visibility of the treatment for the various test conditions. A variety of marking and marker treatments were evaluated under day and night conditions with varying levels of water clarity and water depth. The Task 5 research was used, in conjunction with other project tasks, to recommend an implementation plan on the use of pavement markings and markers at LWCs.

This chapter provides the results of small-scale and full-scale evaluations of pavement marking and marker visibility across a range of test conditions. The small-scale testing was conducted to be able to evaluate a variety of treatments and conditions in an efficient manner. The full-scale testing was conducted to verify the small-scale test results. The following subsections are included in this chapter: evaluated treatments, small-scale testing conditions, small-scale test setup, small-scale test results, full-scale testing, comparison to human factors data, and recommendations.

5.2 TREATMENTS

Pavement markings and markers provide delineation of the traveled way and other critical information, such as the locations of stop lines and crosswalks, to road users. To provide this information, the pavement markings must be adequately visible during the day, at night, and during inclement weather conditions. Retroreflectivity is a standard measurement that is used as a surrogate measure for visibility. A higher retroreflectivity value indicates a more visible (brighter) marking.

Pavement markings may be beneficial at LWCs, serving as a warning of potentially hazardous conditions to drivers or simply aiding in delineating the roadway. These benefits will only be realized if the markings remain adequately visible during the conditions in which they are intended to be visible. Current and emerging technologies have allowed markings and markers to remain visible during heavy rainfall conditions, and some systems even remain visible when submerged under a thin layer of water. Standard pavement markings served as the baseline and were compared to markings designed with the intent of providing greater visibility in rainy conditions. These markings include paint with a wet reflective element, all-weather tape with and without contrast, standard RRPMs, and internally illuminated raised pavement markers (IIRPMs). Figure 5-1 through Figure 5-5 provide images of the treatments.

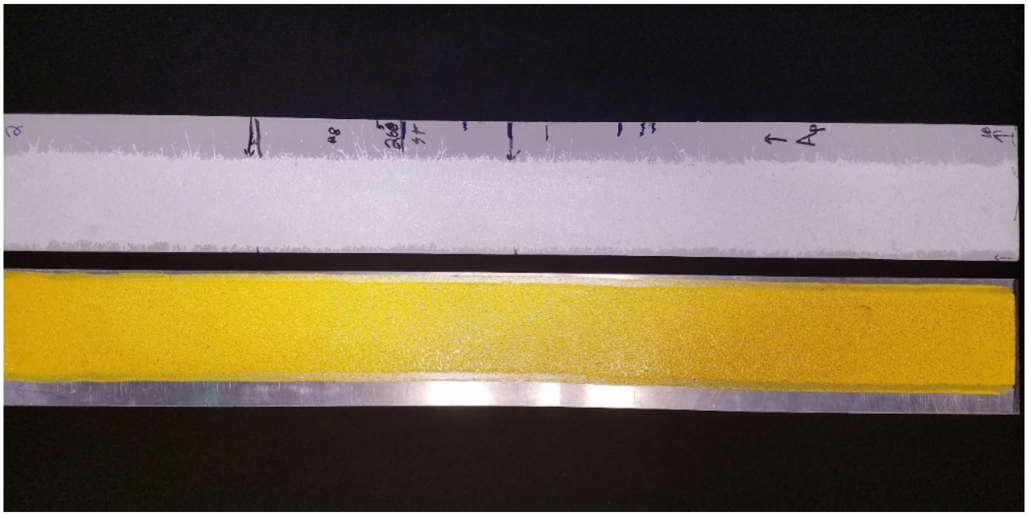


Figure 5-1. Standard Marking Samples.

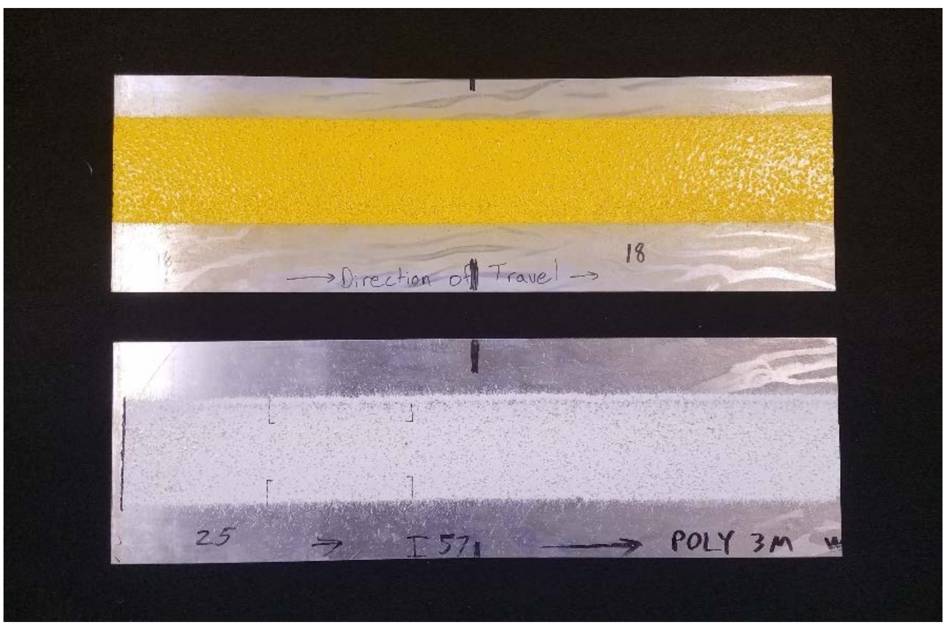


Figure 5-2. Wet-Weather Marking Samples.

Figure 5-3. Preformed Tape Samples.

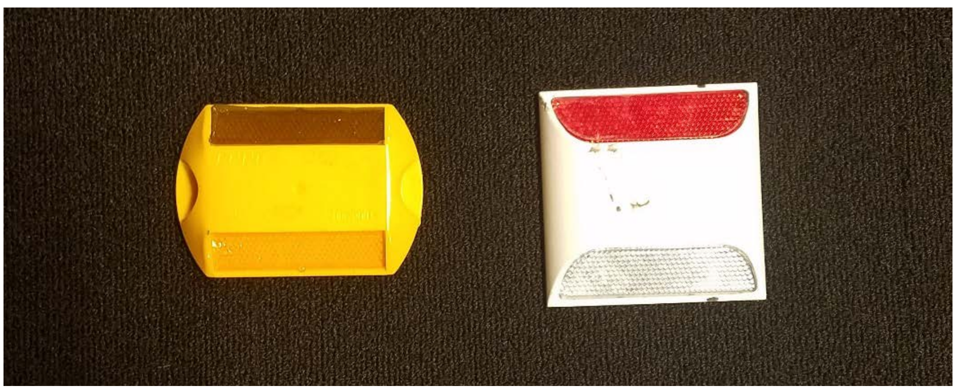


Figure 5-4. RRPM Samples.

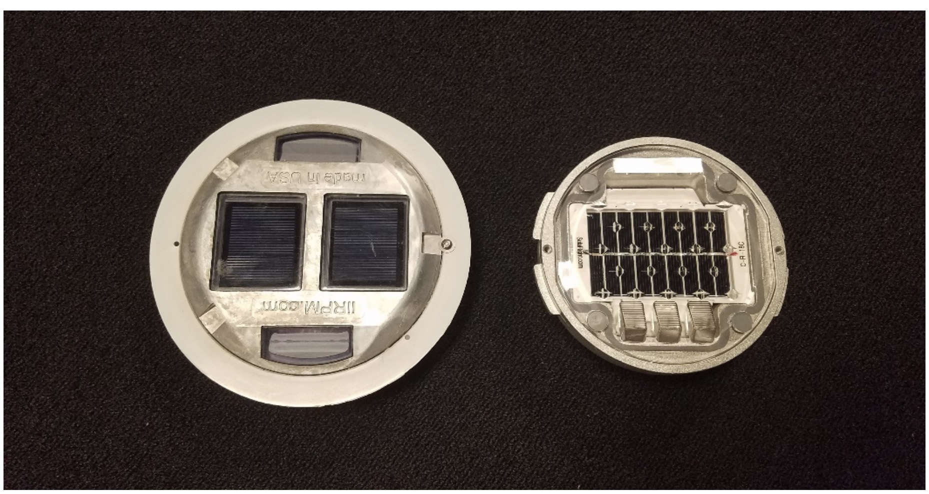


Figure 5-5. IIRPM Samples.

Each of the pavement marking and marker treatments was evaluated in white and yellow due to the visibility differences between the two colors and applications where only one or the other may be utilized. The internally illuminated markers were also evaluated in red due to the ability to turn them on and off during specific conditions and their possible application to indicate to the driver to stop and do not cross. Table 5-1 provides the dry retroreflectivity values of the marking and marker treatments. ASTM E1710, coefficient of retroreflected luminance (R_L), was used to evaluate the dry pavement marking retroreflectivity. ASTM E1696, coefficient of luminous intensity (R_I), was used to evaluate the dry marker retroreflectivity. In addition to the treatment color and retroreflectivity, the road surface plays a role in short- and medium-range visibility. The contrast between the treatment and the road surface, typically described as the ratio of the marking luminance properties to the pavement luminance properties, is a factor for both day and night visibility. For this testing, all the treatments were on aluminum or fiberglass substrate materials for ease of transport and evaluation. Separate specimens of asphalt and concrete road surfaces were evaluated. Figure 5-6 provides an example of the road surface samples evaluated.

Table 5-1. Dry Retroreflectivity Values for Marking and Marker Treatments.

Treatment	Dry Retroreflectivity (R_L or R_I)
Yellow Standard Marking	390 (mcd/m^2/lux)
White Standard Marking	300 (mcd/m^2/lux)
Yellow Wet-Weather Marking	760 (mcd/m^2/lux)
White Wet-Weather Marking	1180 (mcd/m^2/lux)
Yellow Preformed Tape	360 (mcd/m^2/lux)
White Preformed Tape	710 (mcd/m^2/lux)
Black Preformed Tape	8 (mcd/m^2/lux)
White RRPM	785 (mcd/lux)
Yellow RRPM	325 (mcd/lux)

Figure 5-6. Pavement Samples, Concrete (Left) and Asphalt (Right).

5.3 SMALL-SCALE TEST CONDITIONS

Vehicles travel through LWCs at all times of the day and in all weather conditions. The small-scale test conditions considered the time of day, depth of the water over the treatments, and clarity of the water over the treatments. Each of these three conditions influence the visibility of the treatments. Further explanation of the small-scale test conditions is provided below.

5.3.1 Time of Day

The visibility of markings and markers differs greatly between day and night conditions. During the day, the sun provides high levels of illumination, which generally improves visibility of markings but reduces visibility of markers. During daytime, the color of the marking and the contrast of the marking color to the road surface color typically control visibility. At night in rural areas, only the vehicle headlamps provide illumination. The retroreflectivity of the markings and markers will control their visibility at night. For the low-water testing, both day and night conditions are important. The nighttime testing is important for both long- and short-range viewing of the treatments. The daytime testing is important for short-range viewing of the treatments.

5.3.2 Water Depth

The researchers evaluated the treatments in dry conditions and at three water depths. The depths were 1.5 inches of water, 4 inches of water, and 5.5 inches of water. These depths represent water depths at which road users may still try to pass over the roadway. Promoting passage by providing pavement markings with visibility beyond 6 inches of water depth may pose safety issues. The maximum depth where the markings remain visible was also explored. Data were collected while the water was calm and, in some cases, when the water was gently flowing, causing ripples in the water over the treatments.

5.3.3 Water Clarity

The researchers evaluated three water clarity levels. The first level was ~5 nephelometric turbidity units (NTU) to represent clean water. The second level was ~100 NTU to represent somewhat murky water. The third level was ~220 NTU to represent a higher level of murkiness in the water. Higher levels of turbidity, more than 1,000 NTU, are common during major flood events and areas where runoff picks up sediment from agricultural or construction activities. At some point, the turbidity of the water will prevent enough light penetration that the markings will not be visible during the day or night even when only a shallow amount of water is over the marking. Figure 5-7 provides examples of a range of turbidity levels. The researchers added ball clay powder to the water supply tank to achieve the desired turbidity levels.

Figure 5-7. Example of Different Water Clarity Levels.

5.4 SMALL-SCALE TEST SETUP

The unpredictable nature of water flow at LWCs requires the initial evaluation of treatments to take place in a controlled environment. Existing TTI facilities were modified to suit the needs of this project. The small-scale test area and evaluation equipment are described in this section.

5.4.1 Test Area

The researchers used facilities at the TTI sediment and erosion control laboratory to conduct the controlled testing. Figure 5-8 shows the sediment retention device (SRD) that served as the basin for holding the samples and water. Instead of using the SRD to measure retained sediment from the water flowing from the tank, the researchers built a dam across the trough so that the water was held at a constant depth in the evaluation area, with excess water flowing over the top of the dam. Researchers placed treatments at the back of the pooled water on a flat platform built across the bottom of the trough and evaluated the treatments at the appropriate viewing angles. The height of the dam was adjusted to provide the different evaluation depths. The SRD had a 1,600-gallon tank with agitator where water of a single turbidity level was stored for each test. The turbidity of the water was measured at the exit of the tank.

Figure 5-8. Modified SRD Testing Facility.

5.4.2 Evaluation Equipment

The researchers quantified treatment dry retroreflectivity values using handheld retroreflectometers. The dry retroreflectivity value is a surrogate to the visibility of the treatment in a dry condition, with a higher value indicating higher visibility. Markings and markers use different evaluation techniques, and thus the scale of the retroreflectivity measurement between the two treatments is different. A higher retroreflectivity value will allow the treatment to be seen from a farther distance at night and provide a more noticeable difference from the flooded marking condition if the marking is submerged in water.

The researchers used a calibrated state-of-the-art imaging colorimeter to capture treatment visibility information during the testing. The Prometric I29 CCD imaging colorimeter captures a calibrated image of a scene that allowed researchers to analyze each pixel for color and luminance. The imaging colorimeter was mounted on a tripod so the evaluation geometry would be consistent for each evaluation. A light source (sealed beam vehicle headlamp) for the nighttime evaluations was also mounted to a tripod to control the illumination angle during the testing. Figure 5-9 provides an example of the colorimeter and light setup. The colorimeter and light source were positioned to the correct heights to simulate the geometry under evaluation (see next section on evaluation geometry).

Figure 5-9. Day and Night Test Setup.

5.4.3 Evaluation Geometry

The testing was conducted at scale geometry so that the various factors and observation geometries could be evaluated in the most efficient way possible. The intent of the scale testing was to evaluate the impact of the various factors (treatment type, time of day, water depth, and water clarity) efficiently so that full-scale testing could be conducted on only select combinations. This allowed the researchers to take a time- and cost-efficient approach to meet the objectives of the research.

While the actual distance from the markers and markings remained a constant 49.2 ft (15 m), the simulated distances ranged from 49.2 to 600 ft. These simulated distances were 49.2 ft (15 m), 98.4 ft (30 m), 250 ft (76 m), 450 ft (137 m), and 600 ft (183 m). Example images of the various simulated distances can be seen in Figure 5-10 for the day testing of dry marking samples and Figure 5-11 for the night testing of dry RRPM samples. To create these simulated distances, the height of the imaging colorimeter, during the day and night, and the height of the light, during the night, had to be adjusted. These adjustments were based on the ASTM 30-m retroreflectivity geometry standard values used for a vehicle headlamp (2 ft [0.65 m]) and driver eye (4 ft [1.2 m]) heights. Table 5-2 and Table 5-3 provide the height values for each simulated distance. Another required adjustment was the voltage of the headlamp to create the appropriate illuminance value on the targets at the simulated distances. A 2015 Ford Explorer under low-beam illumination on a flat surface at night was used to generate the illuminance value at the different evaluation distances. Illuminance from the vehicle headlamps was evaluated with an illuminance meter at the evaluation distance at locations offset 6 ft (2 m) from the centerline of the vehicle. This yielded the actual illuminance value of each marking (left and right side) in typical driving conditions with a 12-ft (3.7-m) wide lane. The values for each marking position were similar, so the values were averaged. The scaled testing protocol used a single headlamp and positioned the treatments next to each other, so separate illuminance values were not necessary. For each simulated distance, the voltage of the headlamp was adjusted so that the appropriate level of illuminance was provided at the simulated distance. Table 5-4 shows each simulated distance, voltage, and illuminance value.

Figure 5-10. Day Simulated Distance Examples.

Figure 5-11. Night Simulated Distance Examples.

Table 5-2. Light Height for Simulated Distances.

Simulated Distance	Light Height
49.2 ft	2.13 ft
98.4 ft	1.07 ft
250 ft	0.42 ft
450 ft	0.23 ft
600 ft	0.17 ft

Table 5-3. Camera Height for Simulated Distances.

Simulated Distance	Camera Height
49.2 ft	3.94 ft
98.4 ft	1.97 ft
250 ft	0.77 ft
450 ft	0.43 ft
600 ft	0.32 ft

Table 5-4. Voltages Used for Simulated Distances.

Simulated Distance	Voltage	Illuminance
49.2 ft	10.6 v	43.3 lux
98.4 ft	9.4 v	27.1 lux
250 ft	6.5 v	8.1 lux
450 ft	5.1 v	2.9 lux
600 ft	4.45 v	1.6 lux

5.5 SUMMARY OF SMALL-SCALE TEST CONDITIONS

The testing for this task resulted in a variety of treatments and test conditions to consider. Table 5-5 provides a summary of the testing conditions and levels. The treatments and test conditions resulted in the need to perform up to 700 tests, not including testing at maximum depth of visibility and testing for surface disturbances. Each test would include a single treatment, but two variations of the treatment, white and yellow (unless noted otherwise). Not all tests were performed. If a previous test resulted in data that indicated the treatment was no longer visible, subsequent tests were not performed. For example, if the standard marking was not visible at 1.5-inch depth, 250 NTU, 98.4 ft at night, then subsequent depths and distances were not evaluated because visibility would not increase in those conditions. In total, the researchers conducted 160 small-scale evaluations. The results of those evaluations are described in the next section.

Table 5-5. Small-Scale Testing Conditions and Levels.

Factor Level	Time of Day	Depth	Clarity	Evaluation Distance	Treatments (white and yellow)
1	day	dry	N/A	49.2 ft (15 m)	Standard marking
2	night	1.5 in.	~5 NTU	98.4 ft (30 m)	Wet reflective marking
3		4 in.	~100 NTU	250 ft	Wet reflective tape
4		5.5 in.	~220 NTU	450 ft	Wet reflective contrast tape
5		max		600 ft	RRPM
6					IIRPM (white/yellow/red)
7					Road surfaces (ACC, PCC)

5.6 SMALL-SCALE TEST RESULTS

The researchers summarized and analyzed the collected data to allow for comparison of the different treatments across the range of test conditions. The researchers summarized the luminance information separately for the white and yellow treatments for each test condition. Initially, the researchers thought that contrast between the marking and the surrounding pavement would be important. Researchers found that the most important visibility factors were the presence of water for the nighttime testing and the water depth and clarity for the daytime testing. In various combinations of these factors, the treatments were not visible. In this section, the researchers describe the data collected and how the data were used to make recommendations on treatments to support long-range detection of a flooded LWC. Data are also provided to show how the daytime evaluations were used to support recommendations based on short-range visibility of the treatments.

Each test scenario was documented with the imaging colorimeter. Luminance values of the treatments were recorded from each of the images taken. During the daytime, the weather conditions and sun position affected the illuminance from the sun and the resulting luminance from the treatments. Testing was conducted around midday, with limited clouds in the sky. The testing took several hours each day, and tests were conducted over several days. This resulted in the sun changing position in the sky and some variation in the cloud coverage. These changes in illuminance values from the sun did influence individual results, but not the overall trends or resulting recommendations.

Figure 5-12 provides the dry daytime luminance values for the white markings evaluated. The preformed tape had higher values overall compared to the other treatments, indicating it would be the most visible of the treatments evaluated. The daytime luminance is influenced by the quantity and angle of the illuminance from the sun, the diffuse retroreflection properties of the marking, the marking color, and the viewing geometry.

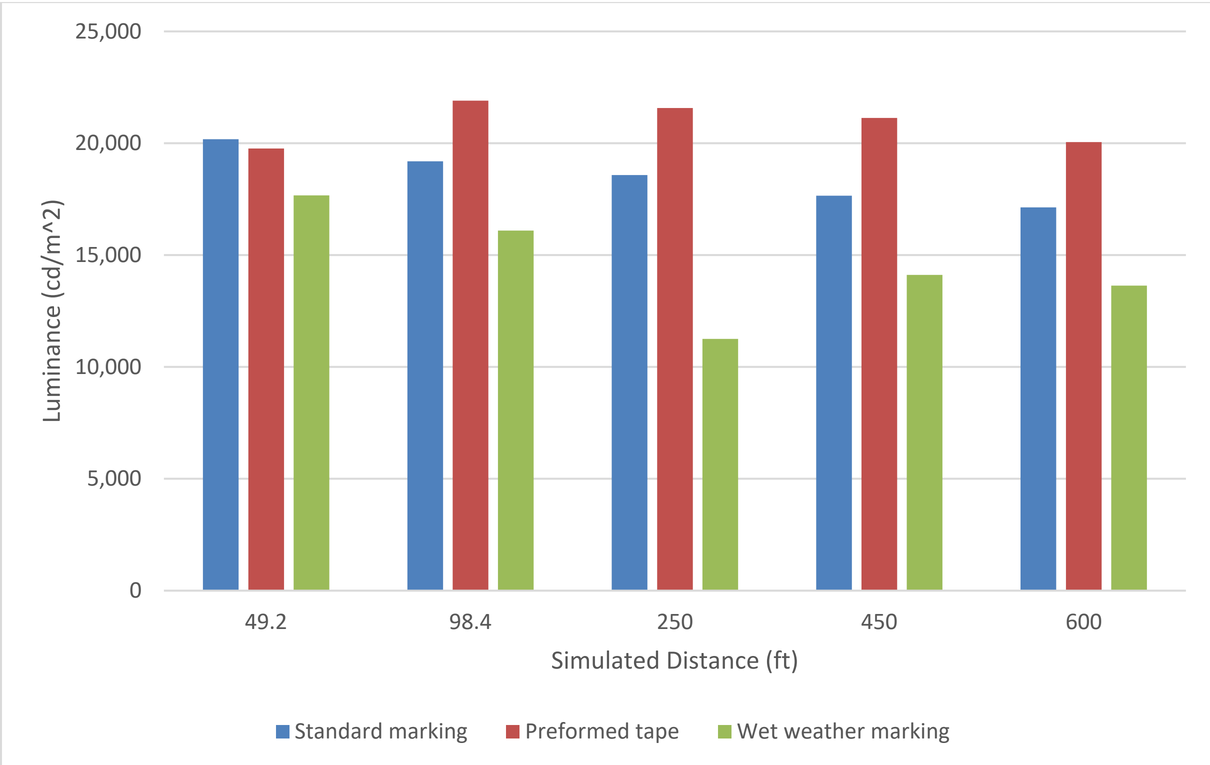


Figure 5-12. Day, Markings, Dry, White Luminance.

Figure 5-13 provides the dry daytime luminance values for the yellow markings evaluated. The preformed tape had lower values overall compared to the other treatments, indicating it would be slightly less visible than the other treatments evaluated. The dry daytime values for either color were not critical to meet the goals of the evaluation. The values are provided for reference purposes to compare to the wet daytime luminance values.

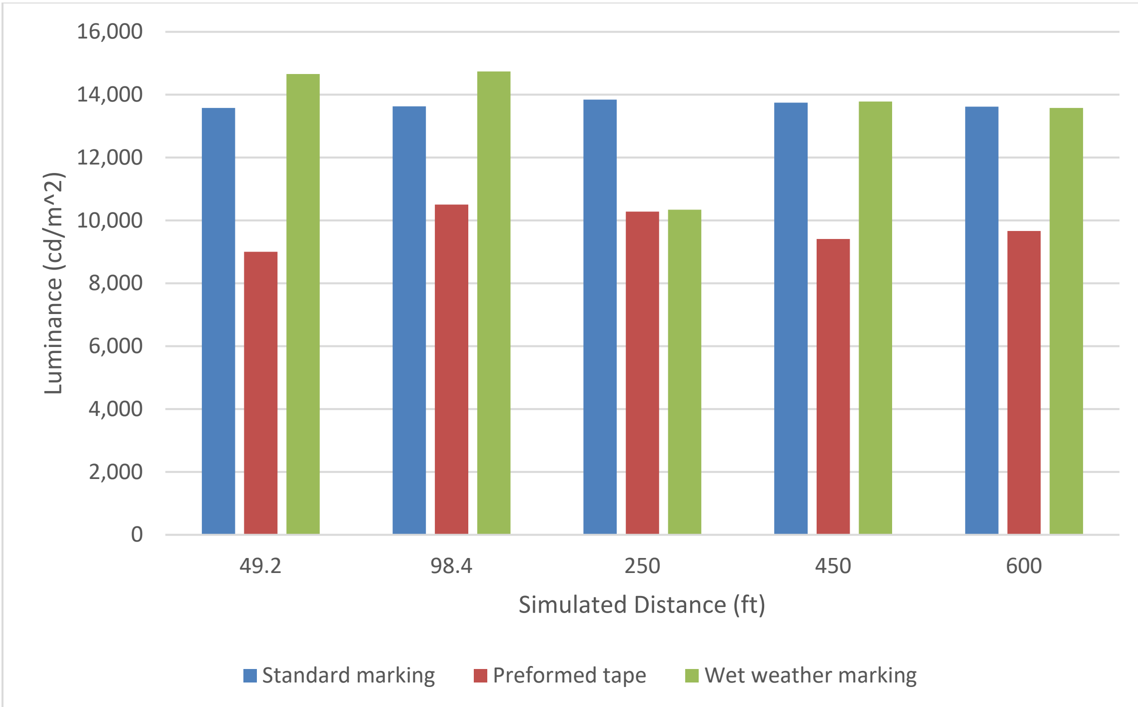


Figure 5-13. Day, Markings, Dry, Yellow Luminance.

Figure 5-14 provides the dry nighttime luminance values for the white markings evaluated. These were important values for the project objectives since the long-range detection and loss of detection of the markings is a feature that can be used to help alert drivers of the presence of water across the road. The decrease in luminance at the farther observation distances was substantial. Pavement markings had limited visibility at night at long observation distances. This decrease in luminance was due to the glancing angle at which the markings were illuminated and viewed (see right images in Figure 5-10), coupled with a lower illuminance provided by headlights at long distances. The wet-weather marking had the highest luminance values, which makes sense because it had the highest retroreflectivity level (see Table 5-1). Figure 5-15 provides similar results for the yellow markings. The actual detection distances provided by these markings in dry conditions are discussed in Section 5.8 in a comparison of the evaluated marking characteristics to human factors detection distance data collected on dry marking visibility.

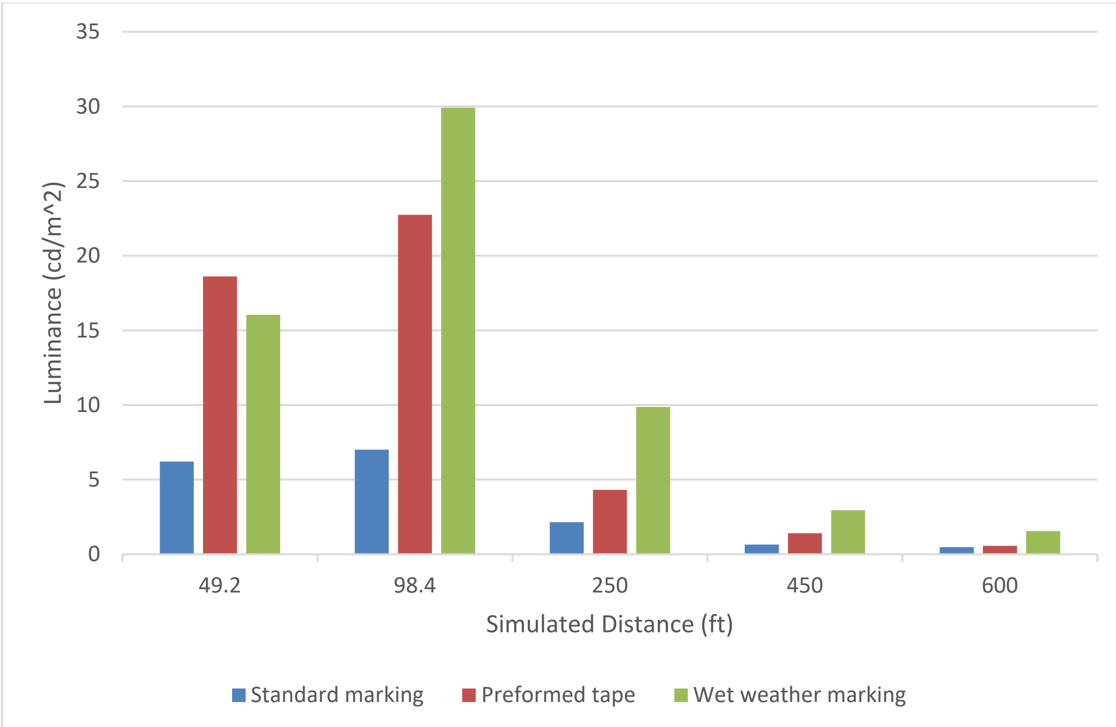


Figure 5-14. Night, Markings, Dry, White Luminance.

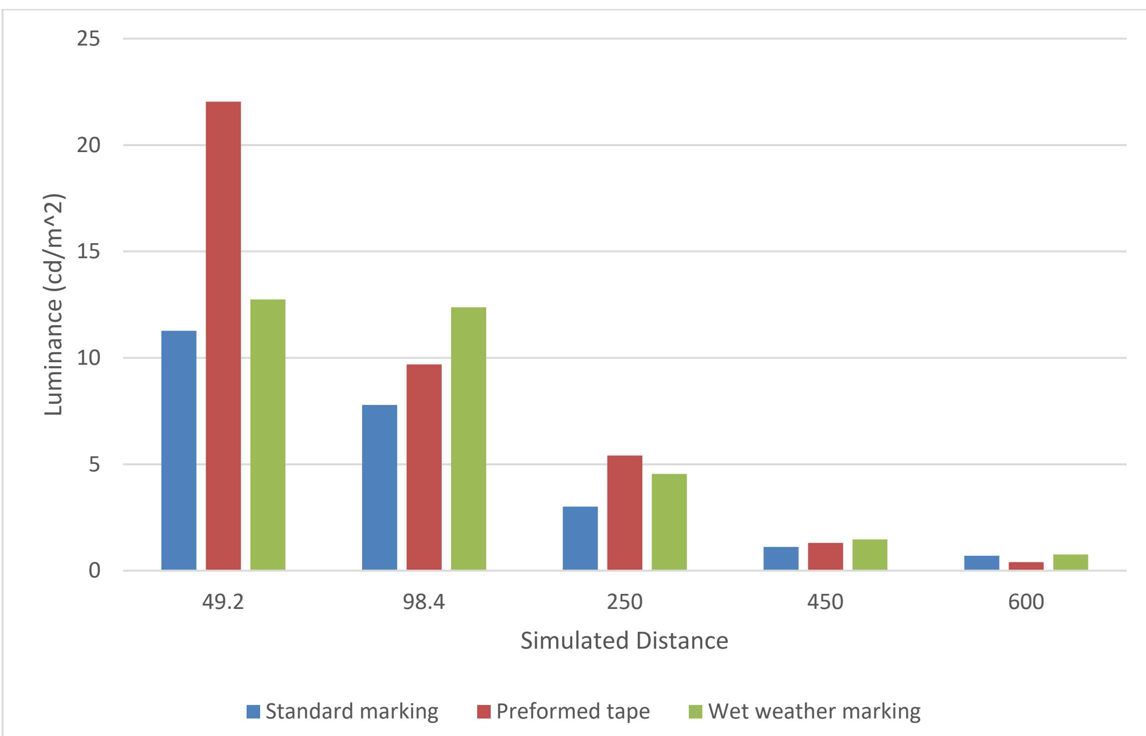


Figure 5-15. Night, Markings, Dry, Yellow Luminance.

During the initial wet testing, the researchers realized that the marking treatments had similar results in both day and night. As a result, the researchers selected the preformed tape to evaluate in all conditions and the other two marking treatments to evaluate in a few of the conditions to verify similar results to the preformed tape data. Table 5-6 provides the luminance values for the preformed tape for each test condition, depth, turbidity, and simulated distance evaluated in the study. Graphs of the data for the white preformed tape marking are provided for visual reference and discussion.

Figure 5-16 shows the daytime luminance data with the lowest turbidity water for the white preformed tape marking. The luminance values were much lower when water was present compared to the dry condition. The values were lower for the 1.5-inch depth compared to the other depths because of lower sun illuminance levels at the time of testing. At the longer observation distances, the marking was barely visible due to the low luminance levels produced.

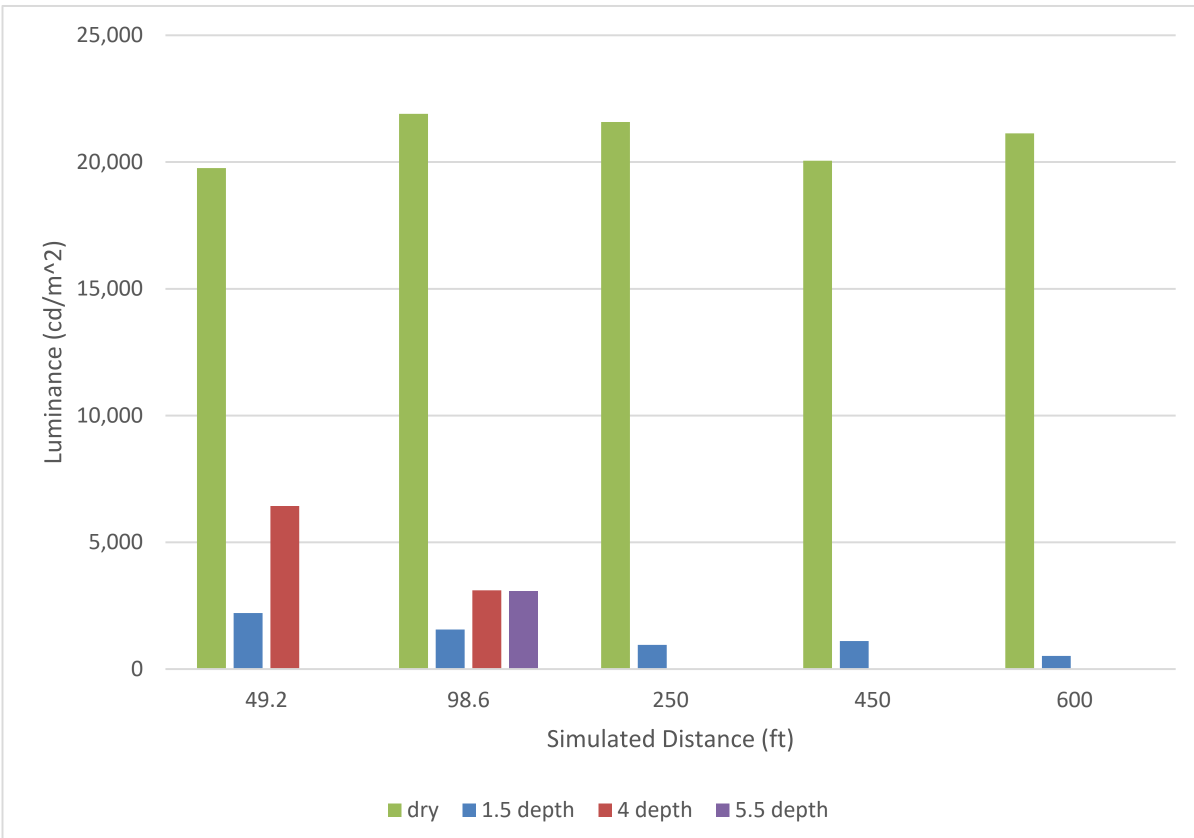


Figure 5-16. Day, Tape, 5 NTU, White Luminance.

Table 5-6. Preformed Tape Luminance Data.

Test Condition	Simulated Distance (ft)	Yellow Luminance (cd/m^2)	White Luminance (cd/m^2)	Black Luminance (cd/m^2)	Dry/Wet	Depth (in)	Turbidity (NTU)
Day	49.2	9,002	19,766	1,758	Dry	N/A	N/A
Day	98.4	10,507	21,902	2,063	Dry	N/A	N/A
Day	250	10,283	21,578	2,144	Dry	N/A	N/A
Day	450	9,663	20,054	2,113	Dry	N/A	N/A
Day	600	9,410	21,134	2,174	Dry	N/A	N/A
Day	49.2	1,412	2,213	196	Wet	1.5	~5
Day	98.4	1,023	1,560	183	Wet	1.5	~5
Day	250	625	958	161	Wet	1.5	~5
Day	450	418	1,109	-	Wet	1.5	~5
Day	600	344	522	115	Wet	1.5	~5
Day	49.2	4,404	6,615	1,279	Wet	1.5	~100
Day	98.4	2,459	3,768	739	Wet	1.5	~100
Day	250	1,045	1,586	0.304	Wet	1.5	~100
Day	49.2	4,113	5,619	2,089	Wet	1.5	~220
Day	98.4	2,386	3,180	1,310	Wet	1.5	~220
Day	98.4	2,316	2,698	1,969	Wet	1.5	~220
Day	49.2	4,139	6,431	537	Wet	4	~5
Day	98.4	2,076	3,106	395	Wet	4	~5
Day	49.2	3,827	5,015	2,336	Wet	4	~100
Day	98.4	2,161	2,768	1,381	Wet	4	~100
Day	250	1,139	1,392	771	Wet	4	~100
Day	49.2	4,174	4,828	3,710	Wet	4	~220
Day	98.4	1,967	3,069	405	Wet	5.5	~5
Day	49.2	3,687	4,322	3,130	Wet	5.5	~100
Day	98.4	1,920	2,264	1,602	Wet	5.5	~100
Night	49.2	22.0	18.6	0.19	Dry	N/A	N/A
Night	98.4	9.70	22.74	0.16	Dry	N/A	N/A
Night	250	5.41	4.32	0.13	Dry	N/A	N/A
Night	450	1.30	1.41	0.09	Dry	N/A	N/A
Night	600	0.40	0.56	0.08	Dry	N/A	N/A
Night	49.2	0.77	0.76	0	Wet	1.5	~5
Night	98.4	0	0	0	Wet	1.5	~5
Night	250	0	0	0	Wet	1.5	~5
Night	49.2	0	0	0	Wet	1.5	~100
Night	98.4	0	0	0	Wet	1.5	~100
Night	49.2	0.76	0.88	0	Wet	4	~5

Figure 5-17 shows the daytime luminance data with the medium level of water turbidity for the white preformed tape marking. The luminance values decreased as the turbidity level increased, and clearly decreased as the depth of the water increased. At the longer observation distances, the marking was not visible.

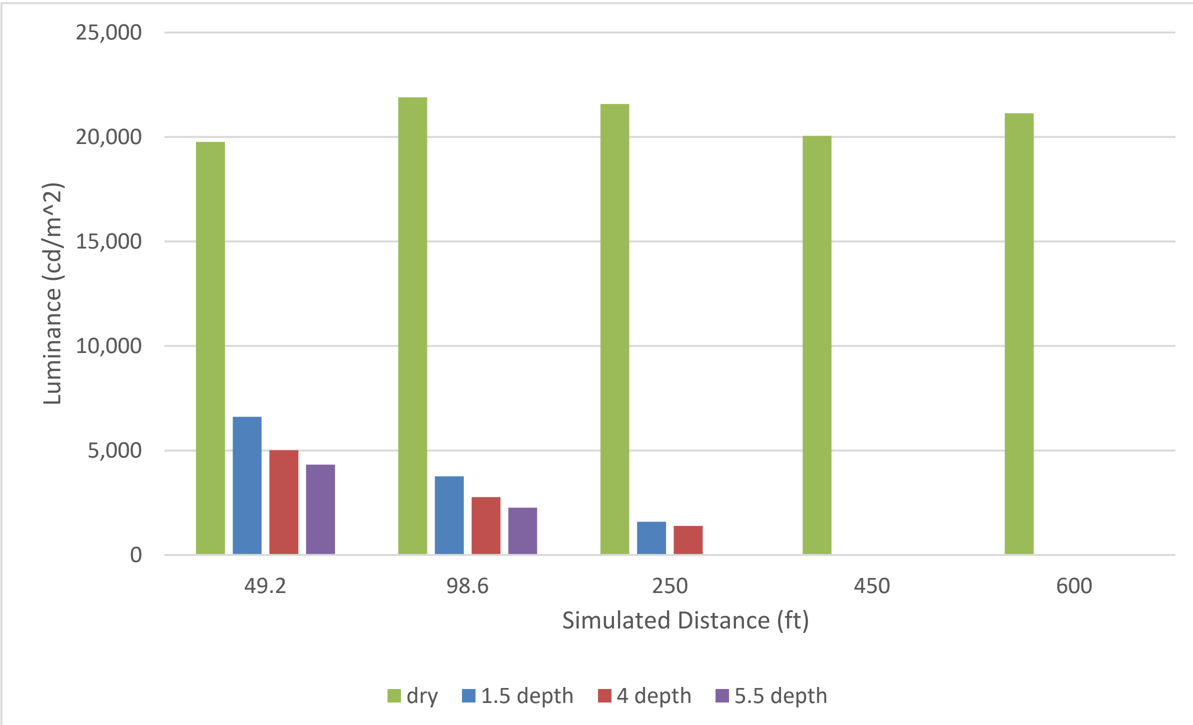


Figure 5-17. Day, Tape, 100 NTU, White Luminance.

Figure 5-18 shows the daytime luminance data, with the highest level of water turbidity for the white preformed tape marking. At the longer observation distances, the marking was not visible. Where visible, the luminance values were reduced compared to the other turbidity levels.

During the nighttime, the preformed tape markings performed as expected when dry but disappeared once these markings had any water covering them. This was the same for each of the pavement marking treatments observed. This finding was due to the water not allowing the light to reach the marking and then be retroreflected back toward the light source. Instead, the water specular reflected much of the light from the headlamps, directing that light away from the observer. The light that did penetrate the water was unable to be retroreflected, thus not allowing the marking to produce visible levels of luminance. Each of the marking treatment's visibility was based on its dry luminance values. When flooded with water, the markings disappeared at the distances and water conditions evaluated. This means that in practice, the markings in a dry condition will be visible for some distance in relation to their retroreflectivity level, and then when submerged in water, they will disappear.

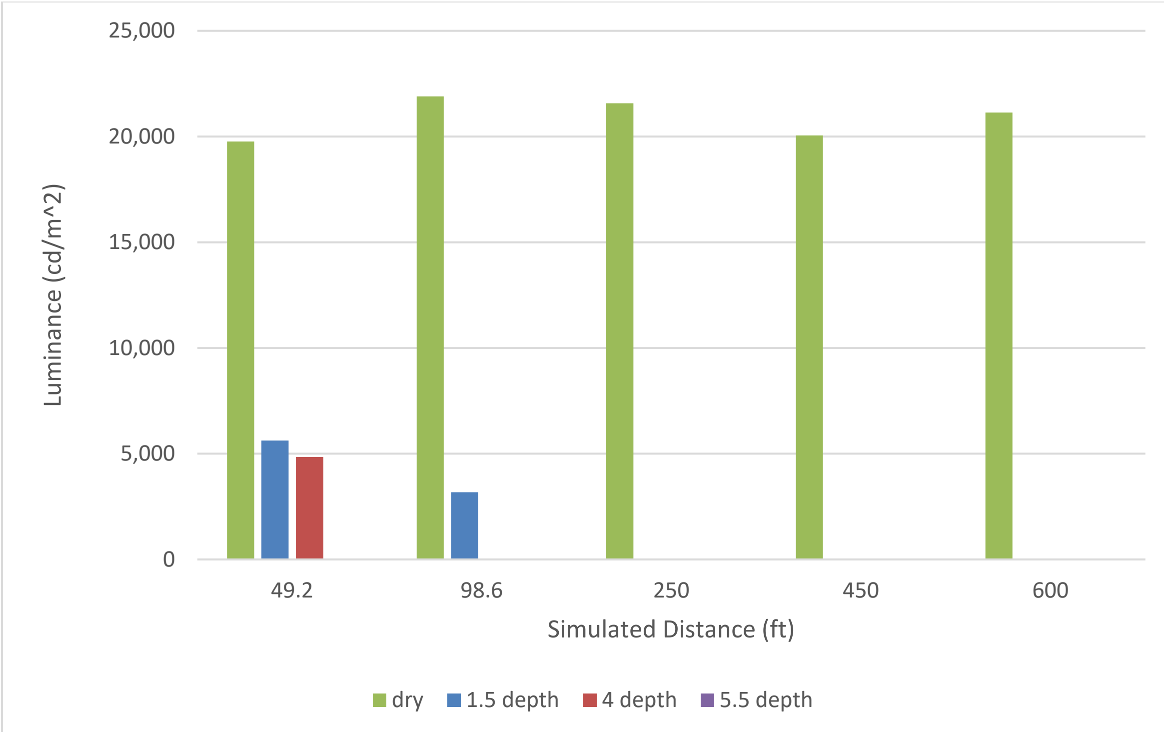


Figure 5-18. Day, Tape, 220 NTU, White Luminance.

Table 5-7 provides a sample of results from the testing that incorporated the surface disturbance during the luminance evaluations. The luminance values fluctuated to give higher values during some trials when the water was moving and lower values during other tests. This fluctuation shows that the amount of luminance fluctuates due to the water reflecting the light in different ways when it is moving as opposed to being mostly still. The daytime evaluations saw minor effects of the surface disturbance. The nighttime evaluations generally saw an increase in luminance as the ripples on the surface allowed the light to penetrate the water and reach the treatments to be retroreflected. This increase in luminance of the treatments due to the surface disturbance increasing light penetration was only observed at the shortest observation distances.

Table 5-8 provides the luminance values for the standard markings for each test condition, depth, turbidity, and simulated distance evaluated in this study. The results agree with those of the preformed tape marking.

Table 5-7. Preformed Tape Luminance with Surface Disturbance.

Test Condition	Simulated Distance (ft)	Yellow Luminance (cd/m²)	White Luminance (cd/m²)	Dry/Wet	Depth (in)	Turbidity (NTU)	Surface Disturbance
Day	49.2	4,404	6,615	Wet	1.5	~100	No
Day	49.2	4,463	7,224	Wet	1.5	~100	Yes
Day	250	1,045	1,586	Wet	1.5	~100	No
Day	250	1,023	1,537	Wet	1.5	~100	Yes
Night	49.2	0.77	0.76	Wet	1.5	~5	No
Night	49.2	1.64	1.58	Wet	1.5	~5	Yes
Night	98.4	0	0	Wet	1.5	~5	No
Night	98.4	0.64	0.93	Wet	1.5	~5	Yes

Table 5-8. Standard Marking Luminance Data.

Test Condition	Simulated Distance (ft)	Yellow Luminance (cd/m²)	White Luminance (cd/m²)	Dry/Wet	Depth (in)	Turbidity (NTU)
Day	49.2	13,581	20,181	Dry	N/A	N/A
Day	98.4	13,629	19,195	Dry	N/A	N/A
Day	250	13,845	18,576	Dry	N/A	N/A
Day	450	13,747	17,659	Dry	N/A	N/A
Day	600	13,620	17,133	Dry	N/A	N/A
Day	49.2	1,305	2,185	Wet	1.5	~5
Day	98.4	1,074	1,608	Wet	1.5	~5
Day	250	575	801	Wet	1.5	~5
Day	450	551	740	Wet	1.5	~5
Day	600	643	1,241	Wet	1.5	~5
Day	49.2	4,324	5,802	Wet	4	~5
Night	49.2	11.3	6.21	Dry	N/A	N/A
Night	98.4	7.79	7.01	Dry	N/A	N/A
Night	250	3.01	2.15	Dry	N/A	N/A
Night	450	1.11	0.65	Dry	N/A	N/A
Night	600	0.70	0.48	Dry	N/A	N/A
Night	49.2	0.91	0.67	Wet	1.5	~5
Night	98.4	0	0	Wet	1.5	~5
Night	250	0	0	Wet	1.5	~5
Night	49.2	0	0	Wet	4	~5

Figure 5-19 shows the daytime luminance of the white standard marking at the lowest turbidity level. The standard marking had similar results and trends to the preformed tape. Visibility was reduced with water over the marking and as observation distance increased.

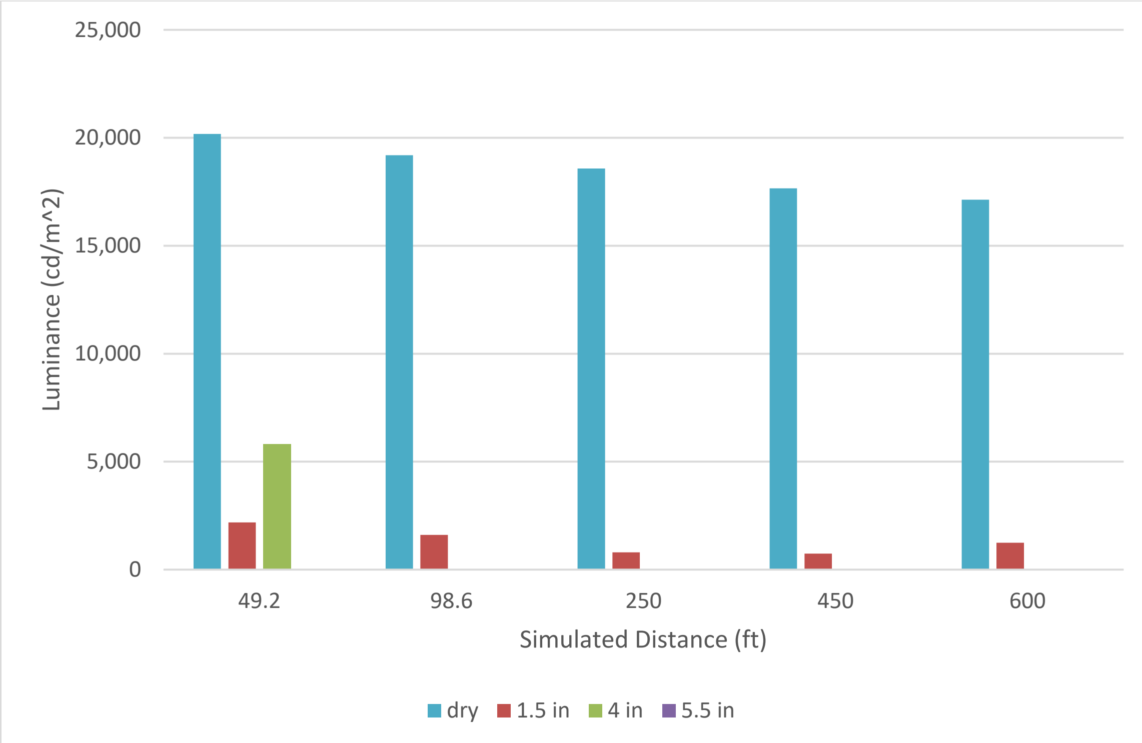


Figure 5-19. Day, Standard Marking, 5 NTU, White Luminance.

Table 5-9 provides the luminance values for the wet-weather markings for each test condition, depth, turbidity, and simulated distance evaluated in this study. The results agreed with those of the preformed tape marking and the standard marking.

Figure 5-20 shows the daytime luminance of the white wet-weather marking at the lowest turbidity level. The wet-weather marking had similar results and trends to the preformed tape and standard marking. Visibility was reduced with water over the marking and as observation distance increased.

Table 5-10 provides the luminance values for the RRPMs for each test condition, depth, turbidity, and simulated distance evaluated in this study. The results indicated that the RRPMs were not as visible as the markings during the day. The results also showed that the markers were more visible at night in the dry conditions. Like the markings, the RRPMs lost nighttime visibility when submerged in water.

Figure 5-21 shows that when the RRPMs were covered by any sort of water during nighttime conditions, they were not easily visible at any distance. At the closest distances, small amounts of luminance were recorded, but not enough for the markers to be easily seen. Like the marking treatments, the RRPM visibility was based on the dry luminance values. When flooded with water, the RRPMs disappeared at the distances and water conditions evaluated. This means that in practice, the RRPMs in a dry condition will be visible for a long distance in relation to their retroreflectivity level, and then will disappear when submerged in water. This is a key finding for developing a marking and marker treatment that may help alert motorists to the presence of water across the road.

Table 5-9. Wet-Weather Marking Luminance Data.

Test Condition	Simulated Distance (ft)	Yellow Luminance (cd/m²)	White Luminance (cd/m²)	Dry/Wet	Depth (in)	Turbidity (NTU)
Day	49.2	14,658	17,674	Dry	N/A	N/A
Day	98.4	14,740	16,097	Dry	N/A	N/A
Day	250	10,343	11,253	Dry	N/A	N/A
Day	450	13,783	14,118	Dry	N/A	N/A
Day	600	13,582	13,638	Dry	N/A	N/A
Day	49.2	1,264	2,070	Wet	1.5	~5
Day	98.4	1,239	1,596	Wet	1.5	~5
Day	250	661	798	Wet	1.5	~5
Day	450	649	1,001	Wet	1.5	~5
Day	600	645	754	Wet	1.5	~5
Day	49.2	4,798	6,190	Wet	4	~5
Night	49.2	12.7	16.0	Dry	N/A	N/A
Night	98.4	12.4	29.9	Dry	N/A	N/A
Night	250	4.55	9.87	Dry	N/A	N/A
Night	450	1.47	2.96	Dry	N/A	N/A
Night	600	0.76	1.55	Dry	N/A	N/A
Night	49.2	0	0	Wet	1.5	~5
Night	49.2	0	0	Wet	4	~5

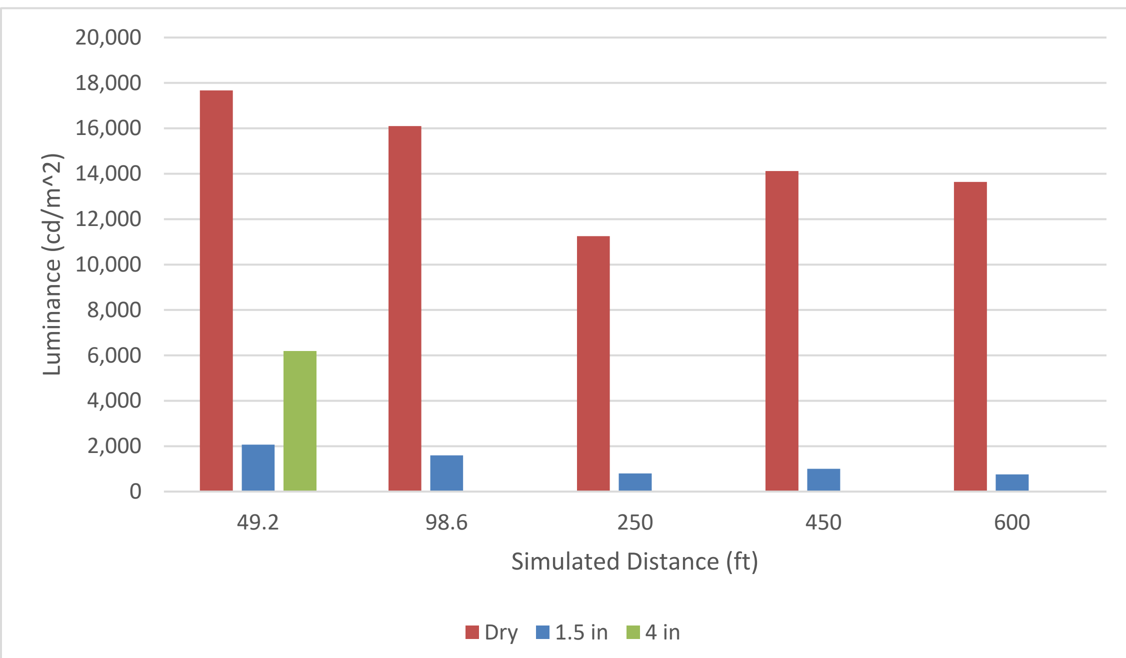


Figure 5-20. Day, Wet-Weather Marking, 5 NTU, White Luminance.

Table 5-10. RRPM Luminance Data.

Test Condition	Simulated Distance (ft)	Yellow Luminance (cd/m^2)	White Luminance (cd/m^2)	Dry/Wet	Depth (in)	Turbidity (NTU)
Day	49.2	7,267	4,852	Dry	N/A	N/A
Day	98.4	7,533	5,355	Dry	N/A	N/A
Day	250	7,557	5,223	Dry	N/A	N/A
Day	450	7,615	5,012	Dry	N/A	N/A
Day	600	7,598	5,115	Dry	N/A	N/A
Day	49.2	0	1,806	Wet	1.5	~5
Day	98.4	0	0	Wet	1.5	~5
Day	250	0	0	Wet	1.5	~5
Day	450	0	0	Wet	1.5	~5
Day	600	0	0	Wet	1.5	~5
Day	49.2	2,417	3,651	Wet	1.5	~100
Day	49.2	2,429	3,093	Wet	4	~5
Day	98.4	1,167	1,510	Wet	4	~5
Night	49.2	136	163	Dry	N/A	N/A
Night	98.4	1,154	1,198	Dry	N/A	N/A
Night	250	414	340	Dry	N/A	N/A
Night	450	180	118	Dry	N/A	N/A
Night	600	105	79.4	Dry	N/A	N/A
Night	49.2	2.87	21.7	Wet	1.5	~5
Night	98.4	0	4.01	Wet	1.5	~5
Night	250	0	0	wet	1.5	~5
Night	49.2	0	0.86	Wet	1.5	~100
Night	98.4	0	0	Wet	1.5	~100
Night	49.2	1.44	8.10	Wet	4	~5

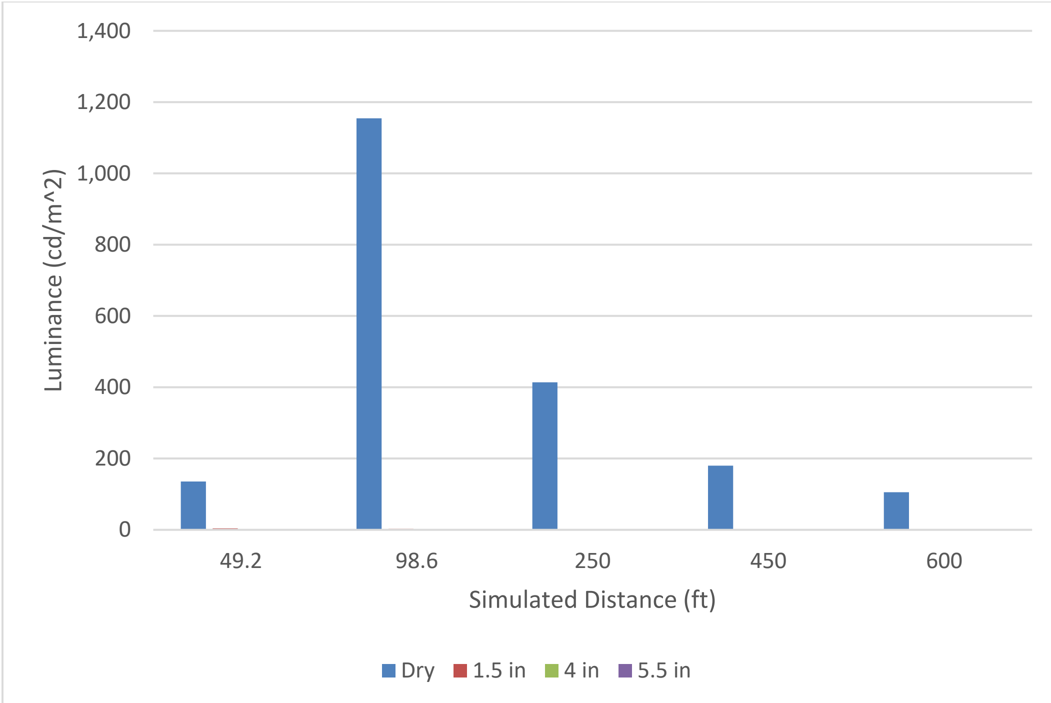


Figure 5-21. Night, RRPM, 5 NTU, Yellow Luminance.

Table 5-11 provides the luminance values for the IIRPMs for each test condition, depth, turbidity, and simulated distance evaluated in this study. Only the yellow and red IIRPMs were evaluated due to the test setup allowing only two to be evaluated at a single time. The researchers did not evaluate the white IIRPM because it is the least likely to be included in any cost-effective recommendations for improving delineation at LWCs. The results indicated that the IIRPMs were not as visible as the markings during the day. The results also showed that the IIRPMs were more visible at night in dry conditions. Unlike the markings and RRPMs, the IIRPMs maintained some level of visibility when covered with water. This is due to the IIRPMs not using the light from the vehicle headlights to produce visibility. The internally illuminated markers produce their only light and thus are not hindered by the lack of vehicle light reaching the treatment. The variation in luminance between the two IIRPMs evaluated and at the different distances is interesting. The IIRPMs are clearly geometry sensitive and may have the capability to have their light output adjusted as specified to meet specific visibility levels.

Table 5-11. IIRPM Luminance Data.

Test Condition	Simulated Distance (ft)	Yellow Luminance (cd/m²)	Red Luminance (cd/m²)	Dry/Wet	Depth (in)	Turbidity (NTU)
Day	49.2	5,669	6,836	Dry	N/A	N/A
Day	98.4	6,617	8,310	Dry	N/A	N/A
Day	250	5,631	16,562	Dry	N/A	N/A
Day	450	6,050	missing	Dry	N/A	N/A
Day	600	6,409	11,537	Dry	N/A	N/A
Day	49.2	0	0	Wet	1.5	~5
Day	98.4	0	0	Wet	1.5	~5
Day	250	0	0	Wet	1.5	~5
Day	450	0	0	Wet	1.5	~5
Day	600	0	0	Wet	1.5	~5
Night	49.2	5,520	8,314	Dry	N/A	N/A
Night	98.4	2,412	3,588	Dry	N/A	N/A
Night	250	2,460	4,728	Dry	N/A	N/A
Night	450	7,301	13,518	Dry	N/A	N/A
Night	600	2,754	3,407	Dry	N/A	N/A
Night	49.2	29.5	39.8	Wet	1.5	~5
Night	98.4	5.03	10.5	Wet	1.5	~5
Night	250	1.39	2.76	Wet	1.5	~5
Night	49.2	7.51	13.1	Wet	1.5	~100
Night	98.4	6.52	7.57	Wet	1.5	~100
Night	49.2	3.10	6.62	Wet	1.5	~220
Night	98.4	1.44	2.36	Wet	1.5	~220
Night	49.2	7.48	14.3	Wet	4	~5
Night	49.2	0.92	1.64	Wet	4	~100
Night	98.4	1.02	1.43	Wet	4	~100
Night	49.2	0.64	1.00	Wet	4	~220
Night	98.4	0.80	0.87	Wet	4	~220
Night	49.2	0.56	0.81	Wet	5.5	~100
Night	49.2	0.48	0.65	Wet	5.5	~220

Figure 5-22 provides a comparison of the dry day luminance values for the yellow IIRPM and the yellow RRPM. The daytime visibility of both treatments was similar, and less than that of the pavement marking treatments. IIRPMs and RRPMs are generally not used for daytime guidance, so this finding is not surprising. Figure 5-23 provides dry night luminance values for the yellow IIRPM and the yellow RRPM. The IIRPM provided higher visibility levels because it was not reliant on headlamps for illumination and not sensitive to the reduced headlamp illumination at the longer observation distances. The IIRPMs were also the only treatment that maintained some level of visibility in the submerged wet night conditions.

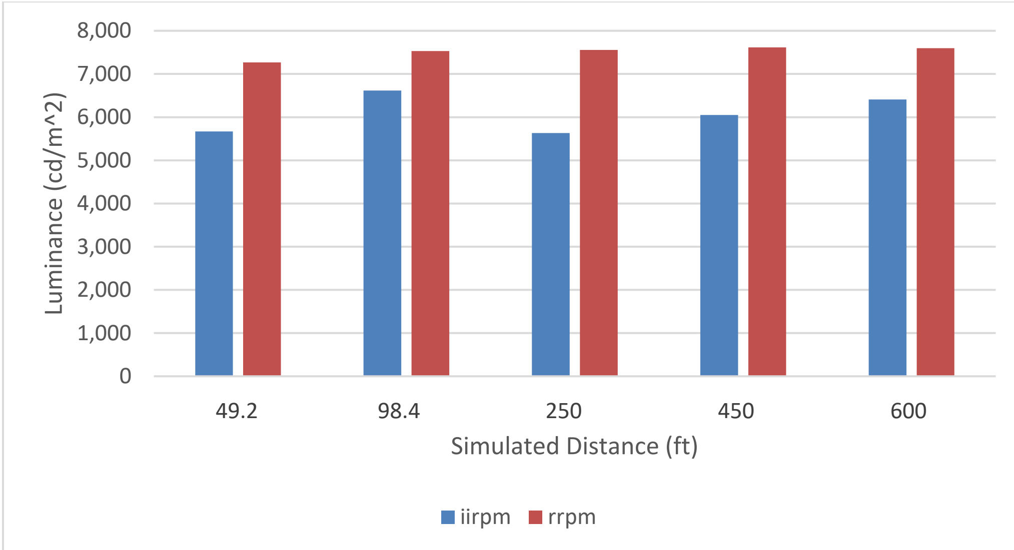


Figure 5-22. Day, Markers, Dry, Yellow Luminance.

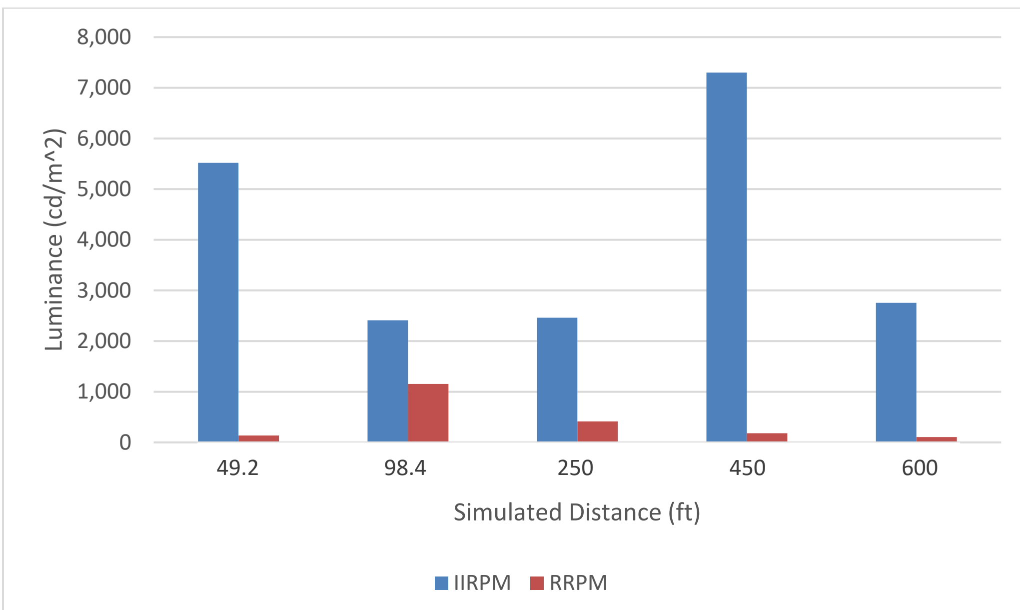


Figure 5-23. Night, Markers, Dry, Yellow Luminance.

5.7 FULL-SCALE TESTING

The small-scale testing was conducted to be able to evaluate a variety of treatments and conditions in a time- and cost-efficient manner. Using the information gathered from the small-scale testing, the researchers conducted a full-scale test to verify the small-scale results. The researchers constructed a mock LWC area and applied markings and markers. The test setup and results are described in the following subsections.

5.7.1 Test Setup

The full-scale testing required the construction of a mock LWC. The LWC was constructed adjacent to a runway at the Texas A&M University System RELLIS Campus. The LWC consisted of a 15-ft-wide and approximately 100-ft-long section of asphalt that was sloped at 0.2 degrees downward. At the end of this slope, a board was placed across the asphalt and attached to the boards that bordered the sides of the asphalt. The boards were used to retain the water for the flooded condition visibility testing. Beyond the board, the LWC continued to a deeper area that was used for the sensor testing portion of the project that is described later in this report. Figure 5-24 shows the mock LWC with water being applied.

Figure 5-24. Mock LWC with Water.

Markings and markers were applied to the asphalt to simulate a travel lane. A portion of the markings and markers were covered with water to simulate the flooded condition, while a portion of the markings remained dry to show the contrast between the flooded and dry portions. A water tank truck was used to supply water for the flooded condition.

A 2015 Ford Explorer was used as the evaluation vehicle for both the day and night (low-beam only) evaluations. The markings and markers were evaluated at the same distances that were simulated in the small-scale testing. These distances were 49.2 ft (15 m), 98.4 ft (30 m), 250 ft (76 m), 450 ft (137 m), and 600 ft (183 m). The same Prometric I29 CCD imaging colorimeter was used to capture the luminance of the markings and markers at the different distances during the day and night evaluations. Figure 5-25 shows the imaging colorimeter in the test vehicle. Figure 5-26 shows the view of the test area from above the test vehicle at 250 ft.

Figure 5-25. Imaging Colorimeter Setup.

Figure 5-26. 250-ft Daytime Evaluation.

5.7.2 Test Results

Images were captured with the imaging colorimeter in dry and flooded conditions during the day and at night for each of the distances. Samples of the images and data are provided to show the results (Figure 5-27 through Figure 5-30). The images collected and analyzed are provided with charts of the luminance along the pavement marking. The luminance charts were created by capturing the luminance information along the pavement markings in each test condition. High luminance values related to a visible marking, whereas low luminance values related to limited or no visibility. In the dry condition charts, the luminance was relatively consistent along the length of the marking. In the flooded condition charts, the luminance started out very low before increasing. The low values indicated the marking was flooded, and the values increased where the marking was dry. This difference between the luminance of the flooded and dry condition supports the findings from the small-scale testing. Figure 5-31 shows the visibility difference at the 600-ft distance between the markings and markers. A 200-mm lens was used to zoom in on the test area to get a clearer picture. The markers that were on the outside of the markings were much brighter and more noticeable. The increased visibility of the markers allows drivers to see a gap in the markers that a flooded condition will create from a longer distance than if just markings are used. This will provide additional warning time to drivers.

Figure 5-27. 30-m Dry Day Evaluation.

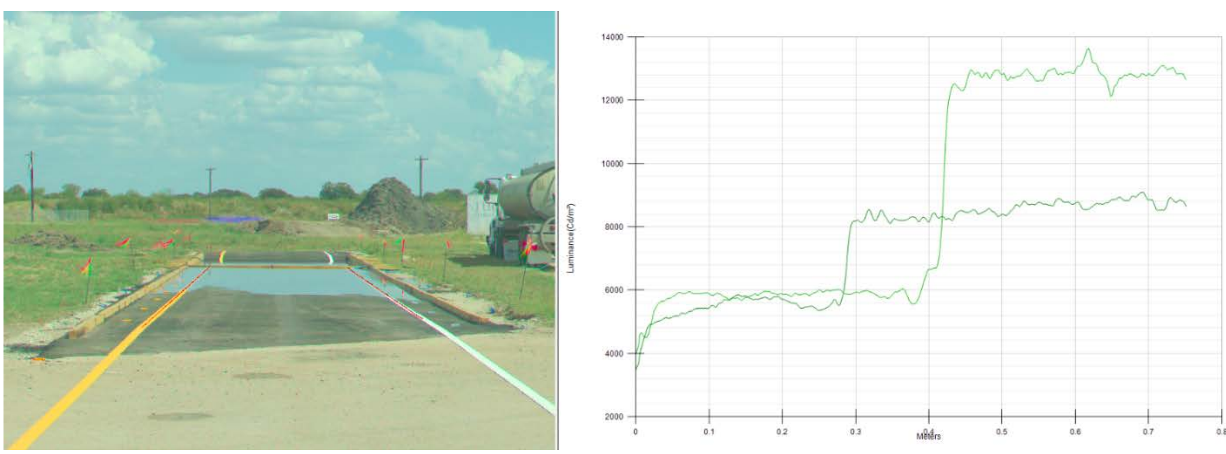


Figure 5-28. 30-m Wet Day Evaluation.

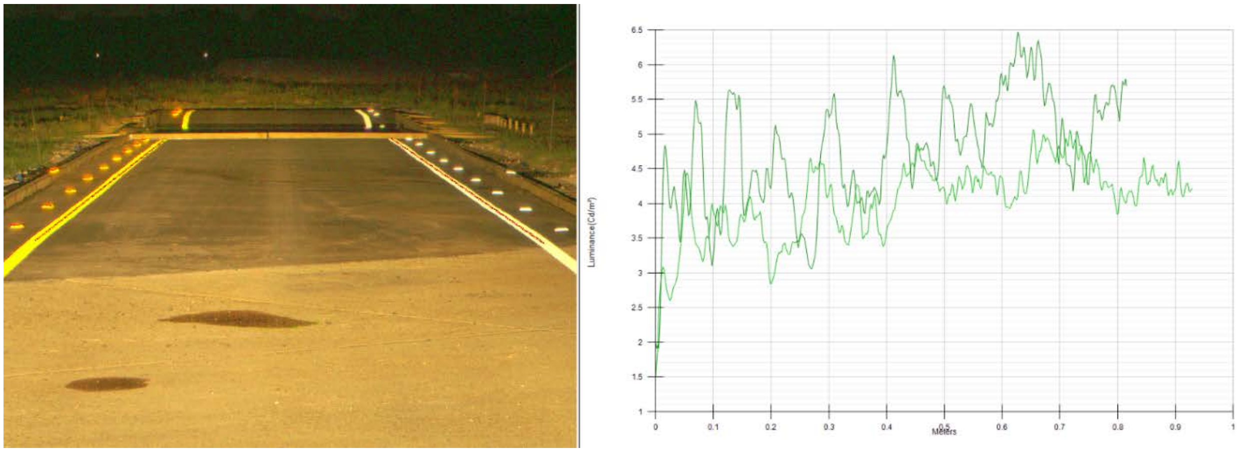


Figure 5-29. 30-m Dry Night Evaluation.

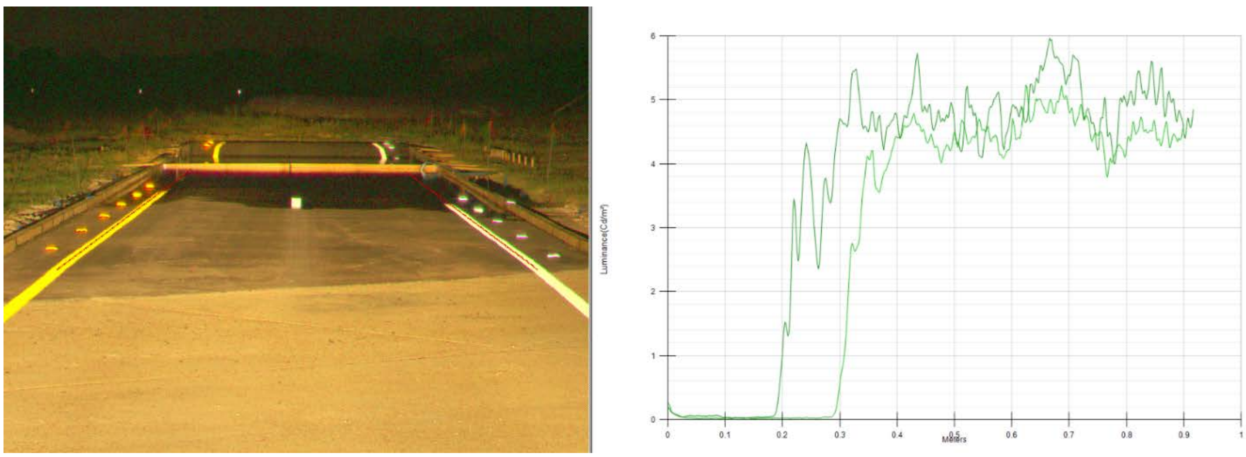


Figure 5-30. 30-m Wet Night Evaluation.

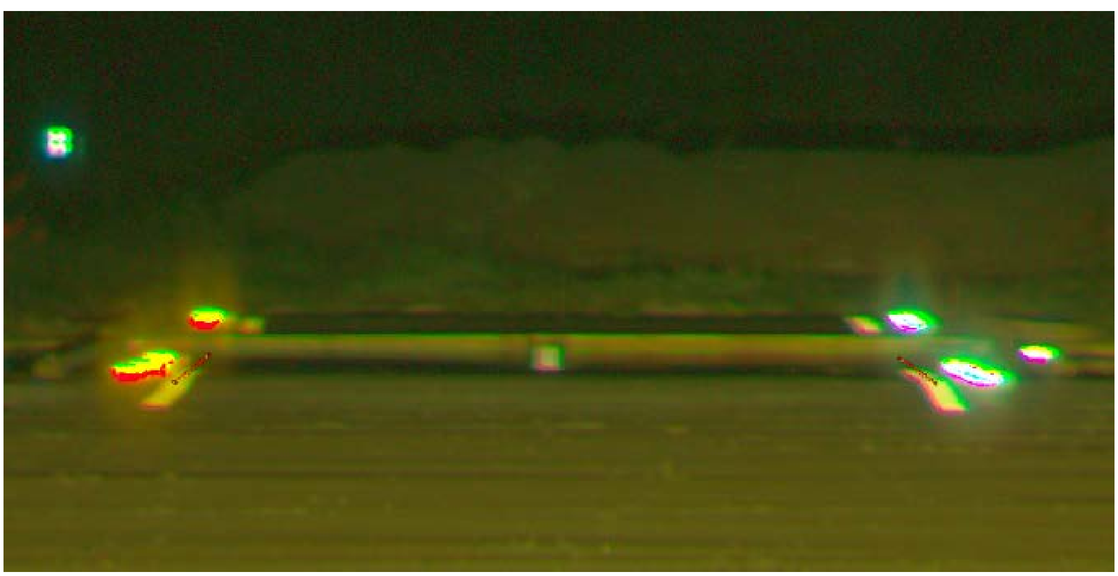
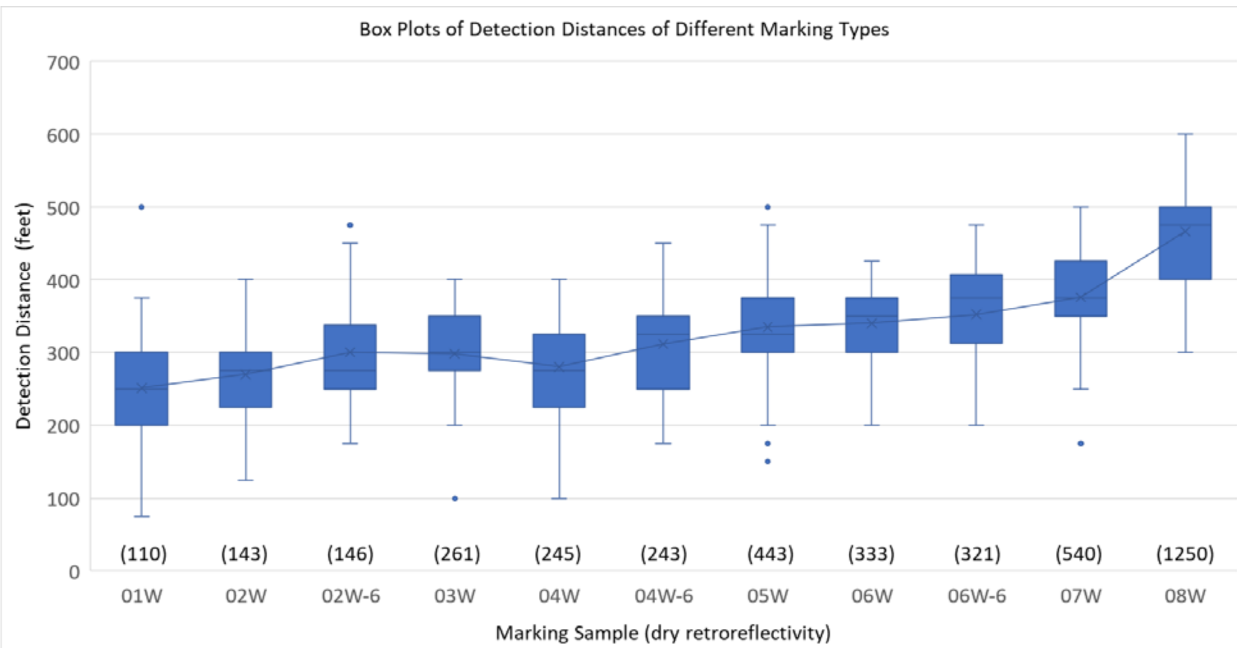


Figure 5-31. 600-ft, 200-mm Lens, Wet Night.

5.8 COMPARISON TO HUMAN FACTORS DATA

The luminance and retroreflectivity data captured in this study did not directly provide visibility information. The luminance and retroreflectivity data both served as surrogates that could be used to compare treatments or could be compared to human factors data, where observers detected markings or markers. Two studies are briefly discussed to provide information on typical detection distances of marking and marker treatments at night.

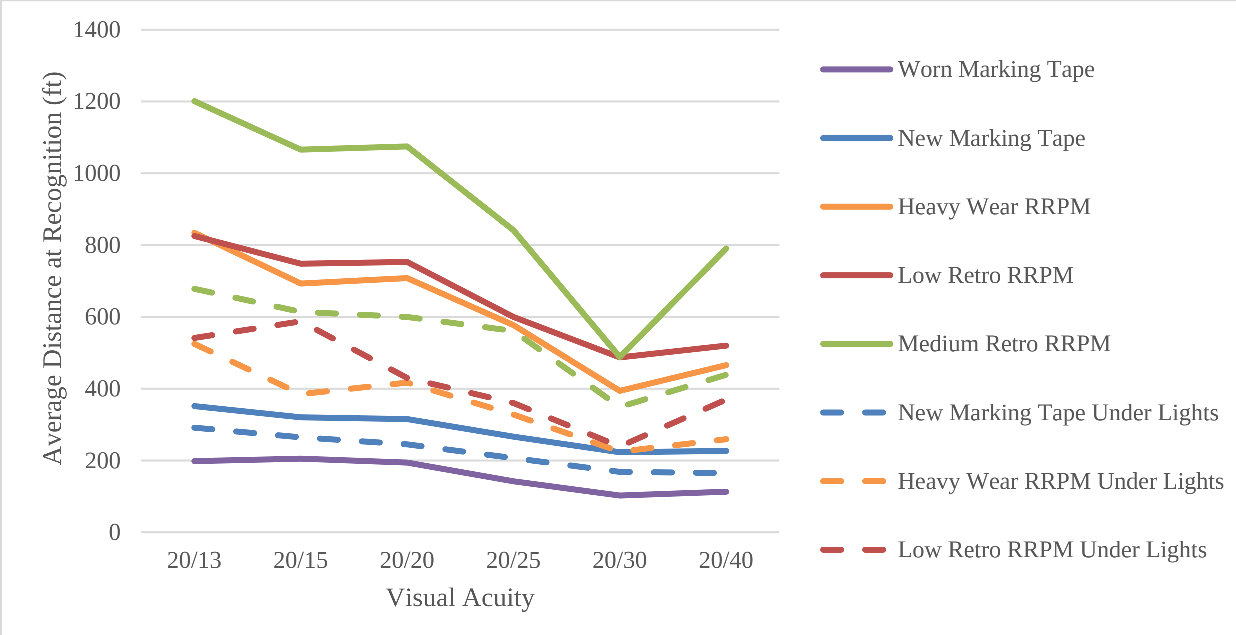
Figure 5-32 provides dry detection distances of pavement markings from a recently published Minnesota DOT research project (*57*). The project used Minnesota drivers with an average age of approximately 60 years. The vehicles driven were 2015 Ford Explorers under low-beam illumination at night. The participants were asked to indicate when they could detect an isolated pavement marking when traveling forward at a low rate of speed. The distances indicated were maximum detection distances at night under low-beam illumination. The findings from the data showed that there were few observations above 500 ft, even for markings with high retroreflectivity levels.



Source: (*58*)

Figure 5-32. Dry Detection Distance of Pavement Markings.

Figure 5-33 provides preliminary data on dry detection distance of pavement markings and RRPMs from an ongoing National Cooperative Highway Research Program (NCHRP) research project (*58*). Table 5-12 provides treatment retroreflectivity levels. The project used Texas drivers with an average age of approximately 56 years. The vehicles driven were 2016 Ford Explorers under low-beam illumination at night. The participants were asked to indicate when they could detect a deviation in the treatment from the centerline of the traveled path while traveling forward at a low rate of speed. The distances indicated were maximum detection distances at night under low-beam illumination. It is clear from the data that the average marking observations were below 400 ft, even for the new markings with relatively high retroreflectivity levels. The RRPMs, on the other hand, produced detection distances more than 1,000 ft in some cases. These RRPMs were all aged to represent various levels of wear.



Source: (*59*)

Figure 5-33. RRPM and Marking Detection Distance by Visual Acuity.

Table 5-12. Retroreflectivity Levels of NCHRP 05-21 Treatments.

Treatment Type	Retroreflectivity
Worn Marking Tape	100 mcd/m^2/lux
New Marking Tape	500 mcd/m^2/lux
Heavy Wear RRPM	30 mcd/lux
Low-Retro RRPM	65 mcd/lux
Medium-Retro RRPM	167 mcd/lux

At 60 mph, approximately 600 ft of visibility is needed for decision sight distance based on rural road conditions (*59*). Under low-beam illumination in dry conditions, pavement markings are unable to provide 600 ft of visibility. RRPMs can provide this level of visibility and thus need to be considered for the long-range detection/warning of flooded roadway conditions.

5.9 RECOMMENDATIONS

The goal of the task described in this chapter was to conduct a study that would allow the researchers to recommend marking or marker treatments that could provide long-range warning of a flooded roadway condition at night while also providing adequate short-range (day or night) visibility to help motorists through the flooded area when conditions permit, but at the same time not provide guidance in situations where the motorist should not cross. Based on the previously described results, the researchers have several recommendations.

The most critical condition addressed in this study is the flooded roadway condition at night. Drivers may not be able to see the water across the roadway in time to safely stop due to the lack of ambient lighting, lack of warning systems, and/or not traveling to roadway conditions. The testing provided results that indicate both the markings and RRPMs evaluated lose visibility when covered with water. This loss of visibility can be used to provide warning that the road is covered with water when the markings and markers are no longer visible. The visibility of pavement markings is generally limited to within 500 ft under low-beam illumination. RRPMs can be used to provide much longer detection distances.

For long-range warning of the flooded roadway condition at night, the researchers recommend applying RRPMs through the areas where flooding conditions may occur and a minimum of 500 ft outside of the potential flooded area on either side. The roadway configuration will govern the type of RRPM used. For two-lane two-way roads, yellow RRPMs should be used along the centerline area. For multilane undivided highways, yellow centerline and white lane line RRPMs should be implemented. For divided highways, white lane line RRPMs should be implemented. Spacing of the RRPMs should be the minimum allowable for the roadway type and marking configuration. This minimum spacing will provide the greatest visibility of the flooded condition by providing a more continuous line of RRPMs that would then be broken by the flooded condition. At problematic locations, RRPMs could be used along the edge line markings to provide additional warning and guidance.

For short-range day and night visibility, the researchers recommend using both white and yellow standard pavement markings throughout the same areas in which the RRPMs would be implemented. These markings will help guide motorists through the LWC area when the water is shallow. At night and in deeper water situations during the day, these markings will be less visible or not visible at all and thus may serve as a deterrent to enter the water because of the lack of visibility. The researchers did not find any benefit to utilizing the more expensive preformed tape or wet-weather pavement marking systems in flooded conditions.

The researchers recommend considering IIRPMs at problematic locations. In areas where drivers regularly drive through high-water conditions and drive off the roadway, yellow IIRPMs could be implemented to improve delineation of the centerline of the roadway. In conjunction with an active warning system for flooded conditions, red IIRPMs and signing could be used to indicate a stop-and-turn-around condition due to flooding. The red IIRPMs could be placed across the lane and activated automatically when flooded conditions limit the safe passage of the roadway. This type of setup would be limited to problematic areas due to the added costs compared to standard markings and RRPMs. This red IIRPM setup would require a request for experimentation from the Federal Highway Administration (FHWA).

Implementing these recommendations will improve visibility of the LWC areas during dry times and help provide warning of and guidance through the areas at times when water is on the road. These improvements will provide safety benefits to drivers at all times of the day and night.

Chapter 6. FLOOD SENSOR AND WARNING DEVICE IDENTIFICATION

6.1 INTRODUCTION

In Task 6 of this study, the researchers conducted a review of commercial flood sensors and high-water warning devices. A metric was developed to evaluate selected flood sensors and warning device combinations. For the flood sensors, a weighting system was developed to judge the priority for incorporating the sensors in Tasks 7 and 8.

6.2 LITERATURE REVIEW

In 2012, the California Department of Transportation (Caltrans) contacted several state DOTs and commercial vendors regarding their flood warning systems. Information on flood warning systems in other states was summarized in a report (*60*). According to the report, Iowa, Georgia, Washington, Illinois, Pennsylvania, Tennessee, Idaho, and Connecticut used or had used a commercial system called BridgeWatch that was developed by United States Engineering Solutions. This system accounts for environmental hazards, seismic events, snow, river flow, and rainfall. The system allows users to set alert-level thresholds and is accessible through a web interface. The state of Washington determined that the cost of the system is $150,000 for setup and then $80,000 annually. Therefore, Washington has discontinued the use of the system for budgetary reasons. Oregon was using a system called BridgeAlerts but was considering switching to BridgeWatch due to the inefficiency of BridgeAlerts. The study found that states were generally unaware of commercial vendors for infrastructure-related flood warning systems other than BridgeWatch, and they were unaware of the existence of such systems internationally.

In 2012, Ostheimer et al. developed flood-inundation maps for Licking County in the state of Ohio by upgrading a lake-level gauge to the existing network and delineation of flood-inundation boundaries that correspond to selected flood stages (*61*). The maps were provided to NWS for incorporation into a web-based flood warning system that can be used in conjunction with NWS flood-forecast data to show areas of predicted flood inundation associated with forecasted flood-peak stages. The report also describes hydraulic modeling using Hydrologic Engineering Center's River Analysis System (HEC-RAS) to establish flood profiles for areas.

The U.S. Geological Survey developed a hydrologic model for wide area flood risk monitoring for the Southern African region (*62*). The model uses daily estimates of rainfall and evapotranspiration derived from remotely sensed data, including rainfall gauge data and satellite microwave data. Model predictive skills were verified with observed stream flow data from locations within the Limpopo basin. The model performed well in simulating the timing and magnitude of the stream flow during an episode of flooding in Mozambique in 2000.

Ford introduced an automated flood-warning decision-support system (FW-DSS) for Sacramento County in the state of California (*63*). The Sacramento County FW-DSS uses off-the-shelf components in a tightly integrated manner to increase warning time. The hardware for the data collection and transmission subsystem is readily available from several vendors in the United States and is priced competitively. Sacramento County installed an automated surface observation system (SOS) to provide real-time information on hydrometeorological conditions. This SOS senses rainfall and water level at approximately 30 sites throughout the county. The

SOS uses tipping-bucket gauges to measure rainfall, pressure transducers and shaft encoders to measure stage, and ultrahigh frequency radios to transmit these observations to a base station. All sensors and transmitters in the SOS conform to the Automated Local Evaluation in Real Time (ALERT) standard that was established by NWS and its cooperators.

Young conducted a research project for the Kansas DOT that surveyed in-situ and ex-situ bridge scour monitoring options (*64*). The research found that scour monitoring options include both portable and fixed instrumentation options. The portable devices are generally divided into three categories: physical probes, sonar devices, and geophysical instrumentation. Fixed instrumentation includes sounding rods, magnetic sliding collars, time-domain reflectometers, fathometers (sonar depth finders), buried sensors (float-out devices), structural sensors (tilt meters), and stream stage gauges. Fixed instrumentation is expensive to install and maintain but may be well suited for high-volume bridges with significant scour risk. Fixed instrumentation can be integrated into a statewide flood warning system for critical locations.

Krajewski and Mantilla deployed a network of 25 sonic stage sensors in the Squaw Creek basin upstream from Ames, Iowa, to determine if the state-of-the-art distributed hydrological model CUENCAS could produce reliable information for all road crossings (*65*). The sensors used in the project were Senix Corporation model TSPC-21S-485 ultrasonic sensors (now replaced by Senix ToughSonic 50). The sensors are potted in 303 stainless steel and are IP-68, NEMA-4X rated, and they operate in 0–100 percent humidity over a temperature range from −40 to +70°C. The sensors have a conical-shaped beam pattern and beam width of 12 degrees, along with internal temperature sensors that are used by the sensors' internal electronics to compensate for changes in the speed of sound with temperature. The sensors also have adjustable sample rates with built-in averaging algorithms. All sensors are preprogrammed at the Iowa Flood Center (IFC) before deployment to average the distance over 15 samples taken 500 ms apart. The average calculated distance computed by the Senix sensor is the value transmitted to the IFC database. The sensors were modified to be able to choose between CDMA and GSM cell networks, produce a more efficient solar charge controller, and remove underutilized local RF communication capability. Figure 6-1 shows the layout of the sensors.

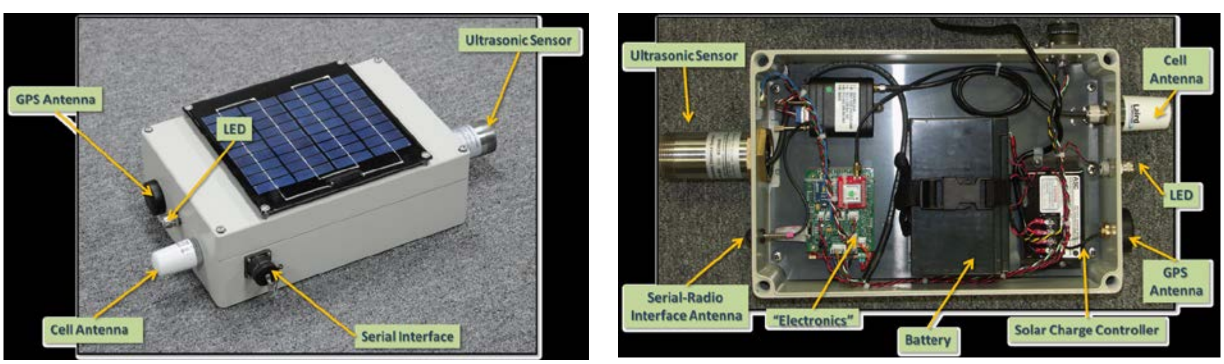


Figure 6-1. Sonic Stream Sensor.

The Traffic & Parking Control Company (TAPCO) developed a flooded road warning system (FRWS) (*66*). The system employs a combination of water detection, solar, wireless, and light-emitting diode (LED) technologies to alert motorists approaching water-covered roads. The system's sensor detects water rising to an unsafe level and immediately sets off TAPCO's BlinkerSign LED lights. The system's signs are linked together so that all signs automatically flash simultaneously when water is detected. Alternatively, the signs can be manually operated by authorities using secure devices and can be activated remotely from a smartphone, computer, or laptop. BlinkerSigns are engineered to withstand harsh conditions. The signs are solar powered and will continue to operate even during power outages. Further, the signs can be placed in remote areas where grid-powered systems are not feasible. Figure 6-2 and Figure 6-3 show this system.

Figure 6-2. Water Detection Sensor and User Monitor.

Figure 6-3. BlinkerSign LED Sign.

Fang et al. introduced the upgrade of the Flood Alert System (FAS), which has been operational for more than a decade and provides accurate advanced warning to the Texas Medical Center in the Brays Bayou watershed of southwest Houston (*67*). The FAS utilizes NEXRAD radar rainfall data (Level II) as input to real-time hydrologic models that generate flow hydrographs as storms progress. The radar rainfall data are calibrated using more than 20 local gauges by Vieux & Associates Inc.

Plessi et al. described the real-time data acquisition, communication, and alerting capabilities of the Flood Frog, an embedded and autonomous device equipped with multiple sensors for environmental and structural monitoring (*68*). A temperature sensor, a vibration detection sensor, and a three-axis accelerometer are embedded in the sensor blocks. The system is capable of operating for several years without human intervention. Battery power and utilization of the GSM mobile network result in a completely wireless system. Coupled with the low cost of the device, this allows deployment in locations where automatic monitoring was previously hindered by cost or infeasibility of installation. Figure 6-4 shows a schematic of the Flood Frog.

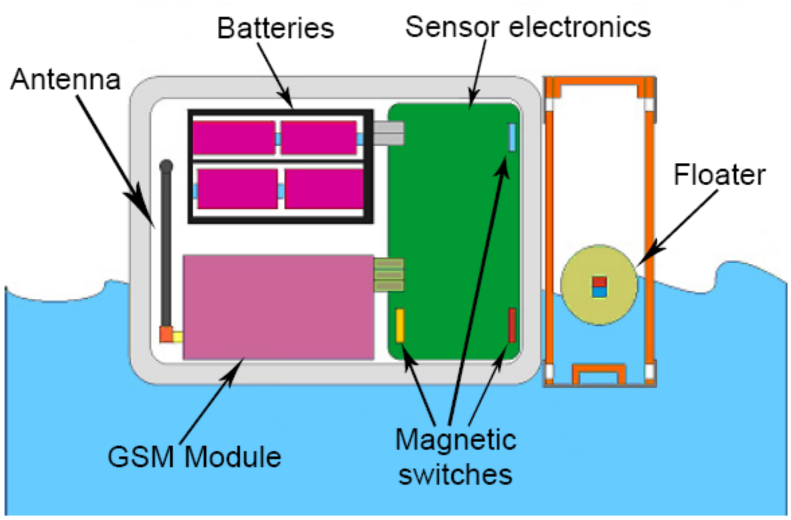


Figure 6-4. Case Design of Flood Frog.

In 2001, Benz et al. documented the capabilities, flooding types, flood events, and equipment reliability of a sensor network system with 29 environmental monitoring stations placed in Houston (*69*). The study found that the transmitters, batteries, and solar panels had the highest rate of failure. The average maintenance periods and service periods of the sensors, which include scheduled and unscheduled maintenance, range from a low of three days to a high of almost 200. The average preventive maintenance period is about 114 days, and the average time between non-scheduled services is 49 days. However, as technology develops, these conclusions may be outdated.

Bosely investigated the potential use of active systems that would automatically warn motorists of hazardous conditions via variable message signs and that could actually close roads with physical barriers (*70*). Vendors and agencies using water-level-monitoring technologies were contacted. The study found that two main types of sensors were used for detecting water level: pressure transducers and ultrasonic devices. Vendors indicated a preference for ultrasonic sensors. However, agencies with sensors in place indicated the pressure transducer sensors could be more durable when protected properly. Other methods for determining water level included an in-pavement sensor or a sensor system utilizing a beam of light. The author concluded that traffic control options included locking cattle-type gates; concrete barriers; railroad crossing gates (quad gates; dual gates—people will go around on the oncoming traffic side); movable barricades (can be moved easily); active warning signs with flashing red lights; variable message signs; and signal preemption (assumes a signalized intersection). Signals should be changed to flashing red, not steady, passive warning signs with water-level indicators.

Burt et al. tested and evaluated both water-level sensors and data logging/recording equipment under outdoor conditions in a comprehensive test (*71*). For the water-level sensors, the authors evaluated robustness, accuracy, cost, power requirements, and ease of calibration.

Some of these sensors require a specific data logging/recording equipment or can be connected to a generic data acquisition system. While the authors performed a comprehensive test of different water-level sensors and data logging/recording equipment devices, the results are outdated because the sensor technology has advanced.

Balke et al. evaluated different high-water warning systems available in the United States (*72*). As part of the project, the authors surveyed DOTs to provide information on the use of automated flood warning systems and included questions with respect to system components and capabilities, system effectiveness, and system maintenance. The outcome of the survey revealed that TxDOT was dissatisfied with the performance of automated flood warning systems. The main reason for the dissatisfaction was the low level of reliability of the systems. The reliability of the system could be improved by providing installation criteria, deployment guidance (type of sensors, communication, and power), and maintenance and testing criteria.

In 2017, Laya Yalamanchili and Satvik Dasari from Canyon Vista Middle School in Austin developed a flood gauge (*73*). Shown in Figure 6-5, the innovative flood warning sensor is named HydroAlert. The device shoots an ultrasonic sensor into the surface of Bull Creek, measuring how far it currently sits from the road. The students also developed a HydroAlert app so that the data can be uploaded every 15 seconds. LED lights on the device change colors (green, yellow, or red) depending on how close the water is getting to the roadway. The cost to build the HydroAlert is less than $100.

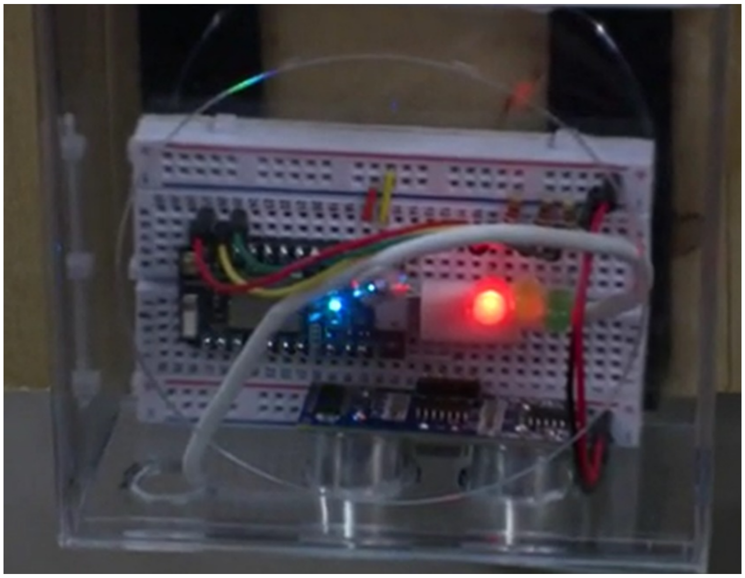


Figure 6-5. HydroAlert Developed by Students at Canyon Vista Middle School.

6.3 FLOOD SENSOR AND WARNING SYSTEMS

6.3.1 Introduction

Figure 6-6 shows an automatic flood warning system consisting of several components:

- Flood sensor.
- Data logging/recording equipment.
- Power supply.

- Data transmission.
- Housing.
- Warning device.

Automated stations can be paired with virtually any active warning device, including gates, barrier arms, or flashing lights.

Figure 6-6. Automatic Flood Warning System (*74*).

Different types of sensors are used for water-level measurements:

- The *potentiometric float and pulley sensor* consists of a float with corresponding counterweight. The float is connected to a pulley wheel via a wire. If the water level changes, the position of the float changes as well, and the pulley wheel rotates. The pulley wheel is connected to a potentiometer that provides a specific resistance with respect to the position of the wheel and the water level.
- The *ultrasonic distance sensor* is a downward-looking measuring system. The ultrasonic distance sensor measures the distance from the transmitter to the water's surface. Ultrasonic pulses are emitted by the ultrasonic transducer, reflected off the water surface, and received again by the ultrasonic transducer. Ultrasonic sensors provide non-contact, accurate, and continuous measurements.
- The *laser distance sensor* works similarly to the ultrasonic distance sensor except that the propagating wave is a monochromatic light wave versus an ultrasonic wave. The advantage of the laser distance sensor is that it can be used in turbulent flow.
- The *radar sensor* operates on a similar basis as the ultrasonic sensor except that radar impulses are emitted. As in the case of the ultrasonic distance sensor and the laser sensor, the radar sensor provides non-contact, accurate, and continuous measurements.
- The *pressure transducer* is submersed in water and relates the water pressure with the water level. The transducer provides high accuracy over a wide range of operating conditions, making it ideally suited to environmental monitoring applications.

- The *bubbler sensor* consists of compressed air, an air flow restrictor, a pressure transmitter, and a sensing tube. The sensor contains no moving parts. Two bubbler sensors can be used to measure the water-level distance of two measurement points.

Table 6-1 shows the weighting factors used to evaluate the flood sensors selected by the researchers.

Table 6-1. Flood Sensor Weighting Factors.

Weighting Factor in %	Applicability	Robustness	Durability	Accuracy	Precision	Repeatability	Ease of Use	Cost	Rating
	20	10	10	10	10	10	20	10	
Sensor 1									
Sensor 2									
Sensor 3									
Sensor 4									
Sensor 5									

6.3.2 Submersible Pressure Sensors

Pressure sensors can measure pressure of liquids. Water pressure increases linearly with depth of submergence. For every 2.31 ft (0.7 m) of water, pressure increases by 1 psi. The pressure difference between the atmosphere and the water around the sensor head produces a force on a flexible diaphragm. Electronics convert the force on the diaphragm into a proportional electric signal.

There are two major methods to read pressure with submersible pressure sensors. Most submersible pressure sensors read gauge pressure (Pg or PSIG), which is the water pressure above atmospheric pressure. Since atmospheric pressure varies with location and time, gauge pressure sensors have a vent tube in the cable that provides a reference to atmospheric pressure. The absolute pressure (Pa or PSIA) includes atmospheric pressure, so the absolute pressure sensors do not have a vent tube.

Table 6-2 summarizes the advantages and disadvantages of submersible pressure sensors. Table B.1 in Appendix B shows the list of pressure sensors reviewed by the researchers.

Table 6-2. Advantages and Disadvantages—Submersible Pressure Sensors.

Advantage	Disadvantage
Easy to install	Damaged by ice
Electronics are hidden from view	Can clog in dirty water
Low power draw	Susceptible to malfunction if often allowed to dry
Not usually affected by air temperature fluctuations	May hang up debris
Not affected by foam	Adversely affected by water temperature fluctuations
Almost no time lag	Range is not adjustable
No delay between the time when power is first applied and the first output	Desiccant must be periodically replaced
	Stilling well often required
	Lightning protection recommended
	Damaged if submerged much too deep
	Easily damaged by aquatic wildlife

6.3.3 Float Sensors

As Figure 6-7 shows, float sensors include two basic types: one involves a pulley and counterweight, and the other uses a spring to produce an upward force on the float cable (*75*). In the pulley and counterweight version, a counterweight provides tension to a beaded cable. If the water level changes, the position of the float changes as well and the pulley wheel rotates. This version of the float sensor is the most difficult to install and calibrate. The pulley has a "travel stop" for both the clockwise and counterclockwise directions. During installation, the user must ensure that neither travel stop will be hit between the highest and lowest expected positions. Additionally, the float must be placed on the correct side of the pulley. Table 6-3 summarizes the advantages and disadvantages of float sensors.

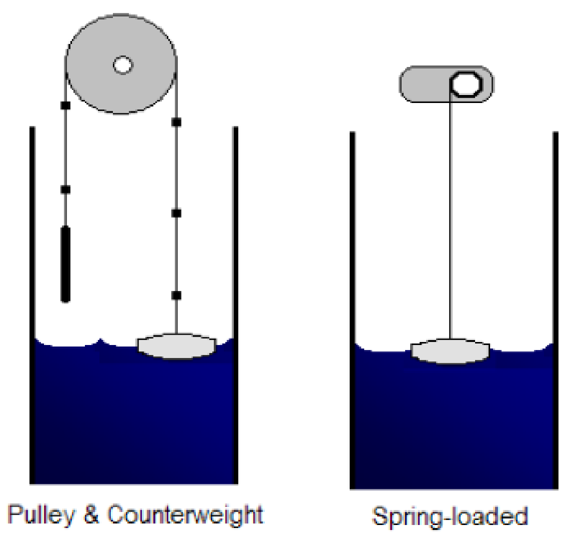


Figure 6-7. Float Sensor Models.

Table 6-3. Advantages and Disadvantages—Float Sensors.

Advantage	Disadvantage
Not affected by dirty water	Stilling well required
Not affected by water temperature	Cable may slip (pulley and counterweight type)
Not affected by foam	Easily vandalized unless enclosed
Low effect of changing air temperatures	May wear if water level remains at one position for extended periods
Low maintenance	Salt build-up may freeze the pulley
Low cost	Some sensors damaged by flooding
Can withstand freezing temperatures	
No delay between the time when power is first applied and the first output	

Researchers reviewed several float sensors from different vendors. Table B.2 in Appendix B shows the list of selected float sensors.

6.3.4 Bubbler Sensors

An air bubbler system uses a tube with an opening below the surface of the liquid level. A fixed flow of air is passed through the tube. Pressure in the tube is proportional to the depth (and density) of the liquid over the outlet of the tube (*75*).

Air bubbler systems contain no moving parts, making them suitable for measuring the level of sewage, drainage water, sewage sludge, night soil, or water with large quantities of suspended solids. The only part of the sensor that contacts the liquid is a bubble tube that is chemically compatible with the material whose level is to be measured. Since the point of measurement has no electrical components, the technique is a good choice for classified hazardous areas. The control portion of the system can be located safely away, with the pneumatic plumbing isolating the hazardous area from the safe area. The system will require a constant supply of air during measurement. The end of the tube should be above a certain height to avoid sludge from clogging the tube.

Table 6-4 summarizes the advantages and disadvantages of the bubbler sensors. The researchers reviewed several bubbler sensors from different vendors. A list of selected bubbler sensors is shown in Table B.3 in Appendix B.

Table 6-4. Advantages and Disadvantages—Bubbler Sensors.

Advantage	Disadvantage
Easy to install and calibrate	May hang up debris
Electronics can be installed away from the water	High list price
Only inexpensive bubbler tubing contacts the water	Sensor output may lag a changing water level
Not significantly affected by air or water temperature fluctuations	Requires a filled large nitrogen tank or a power-hungry air compressor with desiccant packs
Not significantly affected by drying	
Not affected by foam	
Not easily clogged by dirty water	

6.3.5 Ultrasonic Distance Sensor

The ultrasonic distance sensor measures the distance from the transmitter to the water's surface. Ultrasonic pulses are emitted by the ultrasonic transducer, reflected off the water surface, and received again by the ultrasonic transducer. Ultrasonic sensors provide non-contact, accurate, and continuous measurements. Table 6-5 summarizes the advantages and disadvantages of ultrasonic distance sensors.

Table 6-5. Advantages and Disadvantages—Ultrasonic Distance Sensors.

Advantage	Disadvantage
Non-contacting, so not affected by dirty water, floating debris, or aquatic wildlife	Affected by air temperature fluctuations
Not affected by fluctuating water temperatures	May reflect off floating foam or debris
Not affected by high flow rates	Must be aligned precisely
Easy to calibrate	May be affected by turbulent water
Low maintenance	If echo is lost, may display a misleading reading
Excellent linearity and lack of significant hysteresis	Large beam angles cannot be used in constricted spaces
Can withstand freezing temperatures	Some delay between the time when power is first applied and the first output
Long-term reliability	

Researchers reviewed several ultrasonic distance sensors from different vendors, and the list of selected ultrasonic sensors is shown in Table B.4 in Appendix B.

6.3.6 Radar Sensor

Radar sensors are ideal for areas where submersed sensors can be damaged due to corrosion, contamination, flood-related debris, lightning, or vandalism. The sensor emits short microwave pulses and then measures the elapsed time between the emission and return of the pulses. The elapsed time measurement is used to calculate the distance between the sensor and the water. The distance value can then be used to determine depth of the medium. Table 6-6 summarizes the advantages and disadvantages of radar sensors.

Table 6-6. Advantages and Disadvantages—Radar Sensors.

Advantage	Disadvantage
Accurate readings that are independent of dielectric constants, densities and conductivities	Accuracy in measuring fluid levels can be compromised if there is foam build-up from liquid substances
Non-contact with the substance being measured	Blocking distance
Ease of installation and accessibility	Turbulent surfaces may confuse readings
Eliminating any re-setup required	

Researchers reviewed several radar sensors from different vendors, and Table B.5 in Appendix B provides a list of the selected radar sensors.

6.3.7 Flood Warning Devices

The purpose of a flood warning system is to detect and forecast threatening flood events so that the public can be alerted in advance and can undertake appropriate responses to minimize the impact of the event. As mentioned before, there are passive and active warning devices used to warn motorists of potential danger. The passive warnings involve warning signs that indicate that a location on the road may flood or that there might be standing water during heavy rains.

The TxMUTCD provides a series of signs that can be used at LWCs and flood-prone areas (*6*). Figure 6-8 shows TxDOT flood-related weather condition signs.

- ROAD MAY FLOODED sign (W8-18) may be used to warn road users that a section of roadway is subject to frequent flooding.
- WATER CROSSING sign (W8-18aT) is intended to be used at crossings where water is continuously present. A typical application for this sign would be at an LWC; it is not intended to be used on roadway sections that experience periodic flooding.
- WHEN FLOODED TURN AROUND DON'T DROWN sign (W8-18bT) may be used in addition to the W8-18 or W8-18aT sign.

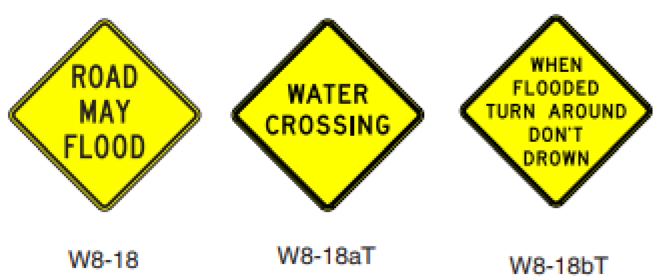


Figure 6-8. TxDOT Flood-Related Weather Condition Signs.

Active devices require automated stations, which can be paired with virtually any active warning device, including gates, barrier arms, or flashing lights.

6.4 CONCLUSIONS

In Task 6, the researchers reviewed and summarized commercial flood sensors and high-water warning devices. Commercially available flood sensors have been used by many DOTs. For instance, Iowa DOT used Senix TSPC-21S-485 ultrasonic sensors as part of the flood warning network. Caltrans used the reactive air level monitor from Tesco Control Inc. for its flood warning system.

Five different types of sensors that are commonly used for water-level measurements were described in this chapter: pressure sensors, float sensors, bubbler sensors, ultrasonic sensors, and radar sensors. The advantages and disadvantages of each type of sensor were summarized for reference. Several commercially available sensors are listed in Appendix B. The researchers found that the sensors' measurement ranges vary from 0 to 100 ft. The researchers also found that price is influenced by accessories and cable lengths. The price range can be $400 to $6,500.

A metric table with weighting factors was developed to judge the priority of the flood sensors. The weighting system consists of applicability, robustness, durability, accuracy, precision, repeatability, ease of use, and cost.

Chapter 7. ASSESSMENT OF FLOOD SENSOR TECHNOLOGY

7.1 INTRODUCTION

The objectives of the flood sensor technology assessment were as follows:

- Evaluate the sensors and devices that are currently on the market, including existing countermeasures for flood sensors.
- Assess existing flood sensors' costs/benefits, including maintenance and applicability in urban and rural areas.
- Develop a metric to evaluate flood sensors.

The metrics to evaluate the flood sensors included applicability (in high-volume and low-volume traffic settings), robustness (e.g., ability to handle freezing), durability (e.g., long-term reliability), accuracy (e.g., performance during fluctuating air/water temperature, dirty water, foam penetration, debris), precision, repeatability (output stability), ease of use (ease of installation, ease of calibration, power requirements), and cost.

Section 7.2 of this chapter describes the water-level sensors further evaluated in this study. The section includes contact as well as non-contact water-level sensors. Section 7.3 describes the experimental setup and procedure to measure the water level under different environmental conditions. The experimental results are evaluated in Section 7.4, while Section 7.5 describes different flood warning devices. Finally, Section 7.6 provides the conclusions.

7.2 DESCRIPTION OF SENSORS

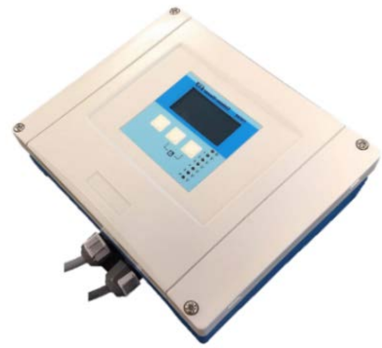
This section briefly describes the physics and functionality of the water-level sensors further examined in this study. Sensor types included ultrasonic sensor, radar sensor, pressure sensor, and wave height gauge.

7.2.1 Ultrasonic Sensor

The ultrasonic sensor is a non-contact measurement device that continuously evaluates the distance beyond the transmitter to the liquid surface. The sensor emits pulses from the ultrasonic transducer, and then these mechanical waves are sent back to the transmitter after reflecting from the medium surface. The distance between the sensor membrane and the liquid surface is calculated according to the elapsed time and the wave velocity as the sensor sends a pulse and receives it back.

The ultrasonic sensor appears to be ideal for the precise measurement of the surface level of both clean and slurry water. Figure 7-1a shows the Endress & Hauser FDU91 ultrasonic sensor, which can detect up to 33 ft from the liquid surface with an accuracy of ±0.08 inches, while Figure 7-1b displays the FMU90 data acquisition system for the FDU91 sensor. Additionally, Figure 7-2 shows the Senix ToughSonic 14 ultrasonic sensor, which can sense 19 ft less compared to the Endress & Hauser FDU91 (*76*).

a) Endress & Hauser FDU91



b) Transmitter FMU90

Figure 7-1. Ultrasonic Sensor.

Figure 7-2. Senix ToughSonic14 Ultrasonic Sensor. (*76*).

7.2.2 Radar Sensor

The radar sensor is another type of water-level sensing technology. The sensor operates in a similar manner to the ultrasonic sensor. The device reports the targeting distance based on analyzing the propagation of microwaves.

Figure 7-3 shows the Endress & Hauser FMR20 radar sensor, which is specifically designed to determine water and wastewater level. In addition, the device supports wireless technology with Bluetooth, which eases operation in the field. The Endress & Hauser FMR20 radar sensor detects up to 33 ft from the medium surface, with an accuracy similar to the Endress & Hauser FDU91 ultrasonic sensor. Worth noting is that the radar sensor provides non-contact, accurate, and continuous measurements similar to the ultrasonic distance sensor.

Figure 7-3. Endress & Hauser FMR20 Radar Sensor.

7.2.3 Pressure Sensor

Pressure sensors are widely used level sensing technology to manage the water level in tanks and vessels, control the amount of gas used in the exhaust system, and record patients' health (*77*). The principles used in pressure sensors are defined based on converting mechanical energy into electrical energy. The pressure of water is known to increase with the depth, meaning 1 psi water pressure equals 2.31 ft liquid height. When the pressure transducer submerges in water, the hydrostatic pressure is provided as the pressure difference between the ambient and the sensor head stimulated by a piezoelectric crystal embedded in the sensor. The crystal has unique properties that aid the smart material in converting the mechanical energy into an electrical signal (see Figure 7-4). Pressure sensors typically give a reasonable degree of accuracy over a set range of operating circumstances, making them ideally suitable for environmental monitoring applications.

Describing the measurement of the pressure in two different classes, namely statics and dynamics, is common. A pressure measurement is called static if it is taken in a stagnant fluid (e.g., water in a stationary tank). The pressure measurement is known as dynamic if it is performed in a non-stationary medium. The height evaluation of sloshing waves in a moving tank exemplifies such a dynamic pressure measurement. In addition, it is common to refer to the static pressure as the pressure head in the literature. The pressure head is solely a function of the height, h, as well as specific weight density, γ, of the liquid. This means the hydrostatic pressure at the same depth differs for dissimilar fluids and increases as the fluid level rises. Figure 7-5 shows a gauge pressure sensor, which is a common device to determine the differential pressure between the ambient and reference pressure.

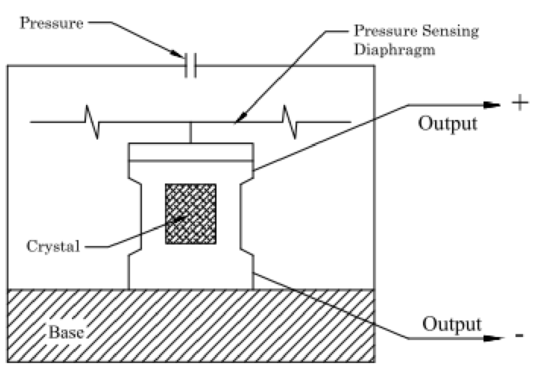


Figure 7-4. Piezoelectric Pressure Transducer.

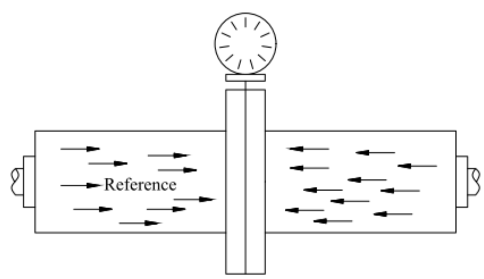


Figure 7-5. Differential Pressure Sensor.

Figure 7-6 depicts the Seametrics PT2X pressure sensor, which is suitable to use in water, wells, and tidal walls. Since the pressure sensor is fabricated with 316 stainless steel, fluoropolymer, and polytetrafluoroethylene, the manufacturer has guaranteed the high corrosion resistivity of the device (*78*). The Seametrics PT2X measures up to 11 ft from the targeting surface with very high accuracy, namely ±0.1 percent.

Figure 7-6. Seametrics PT2X Pressure Sensor (*78*).

7.2.4 Wave Height Gauge

The wave height gauge continuously measures the level of unidirectional and multidirectional waves with great accuracy. The sensor measures the depth of the liquid based on the capacitance change in the probes. In this regard, the growth of the water level contributes to an increase in the sensor capacitance because the relative dielectric constant of water is much greater than that of air. The dissimilarity of the sensor capacitance will be recorded by the gauge and will be translated by the data acquisition system into the measured value of water depth.

Figure 7-7 shows the Akamina AWP-24-SP data acquisition system, as well as the wave height gauge. The wave probe head is the only part of the system to be immersed in water and can be fixed with both stable and movable structures. The support for the probes is made of stainless steel, and a coaxial cable connects the sensor probes to the BNC connector on the AWP 24. The Akamina AWP-24-SP wave height gauge senses up to 2 ft with an accuracy of 0.15 percent.

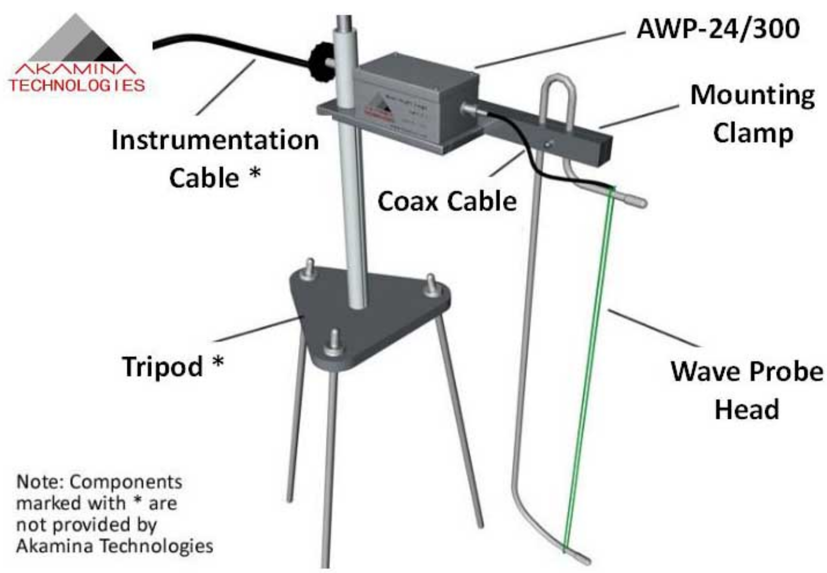


Figure 7-7. Akamina AWP-24-SP Wave Height Gauge (79).

7.2.5 Summary and Technical Specifications

The first class of the sensors reviewed was non-contact measurement devices. Ultrasonic and radar sensors are examples of non-contact sensing devices that measure a distance between themselves and the surface medium. Two ultrasonic sensors were selected to estimate the depth of water: the Endress & Hauser FDU91 and the Senix ToughSonic 14. In addition, the Endress & Hauser FMR20 was selected as a radar sensor.

The second class of sensors reviewed was measurement devices (i.e., the pressure sensor and wave height gauge). The Seametrics PT2X measures a level of water with great accuracy, yet it is not able to sense a distance more than 11 ft. Conversely, the wave height gauge is not able to detect more than 2 ft water depth; however, the sensing device is designed to capture the fluid depth in turbulent and wavy water.

Table 7-1 summarizes the technical specifications of the reviewed sensors based on the available data from manufacturer brochures and factory manuals.

Table 7-1. Technical Specifications of Water-Level Sensors.

Flood Sensors	Price ($)	Range (ft)	Temp. (F)	Power Supply (VDC)	Accuracy	Output
Ultrasonic Sensor: Endress & Hauser FDU91	567	0–33	−40 to 176	10.5–32	±0.08 in.	4–20 mA
Ultrasonic Sensor: Senix ToughSonic 14	505	0–14	−40 to 158	24	±0.2%	4–20 mA
Radar Sensor: Endress & Hauser FMR20	940	0–33	−40 to 176	10.5–32	±0.08 in.	4–20 mA
Pressure Sensor: Seametrics PT2X	1,400	0–11	5 to 131	12	±0.1%	RS485
Wave Gauge: Akamina AWP-24-SP	813	0–2	14 to 122	8–20	±0.15%	NA

7.3 EXPERIMENTAL PROGRAM

To identify the capabilities and robustness of the flood sensors discussed in the previous section, the researchers conducted an acrylic cylinder (AC) test, water tank (WT) test, and field test at the Texas A&M University System RELLIS Campus.

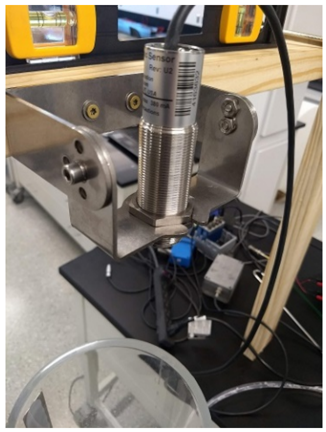
7.3.1 Acrylic Cylinder Test

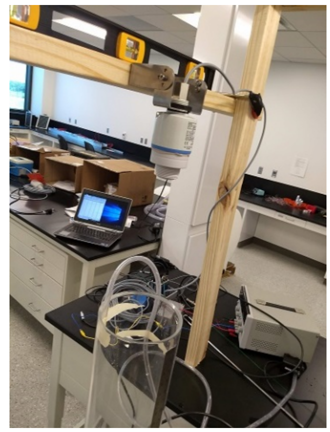
Primary sensor performance was evaluated via the AC test, which was developed to verify if sensors are properly calibrated. Moreover, this experiment provides additional information to assess the degree of precision of the sensor output, as well as to study the long-term stability of device recordings.

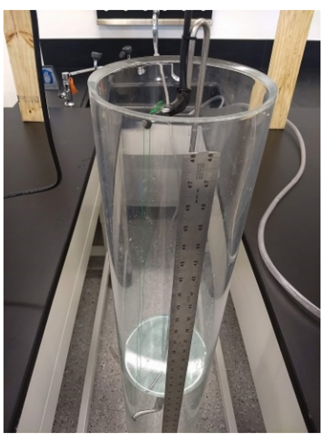
7.3.1.1 Experimental Procedure of AC Test

The procedure for the AC test began with filling the container with pure water up to 4 ft. The water level was recorded for every 2 inches of rise at room temperature. In addition, the technicians simultaneously logged the height of the liquid and the sensor output at every 2 inches as the water drained away from the cylinder. This experiment began with securing ultrasonic sensors in a bracket, as shown in Figure 7-8a and Figure 7-8b. After recording data registered by these sensors, technicians repeated the measurement procedure for the radar sensor. Figure 7-8c shows the setup of the radar sensor and its position at the top of the acrylic container.


a) Endress & Hauser FDU91 Ultrasonic Sensor


b) Senix ToughSonic14 Ultrasonic Sensor


c) Endress & Hauser FMR20 Radar Sensor


d) Akamina AWP-24-SP Wave Height Gauge

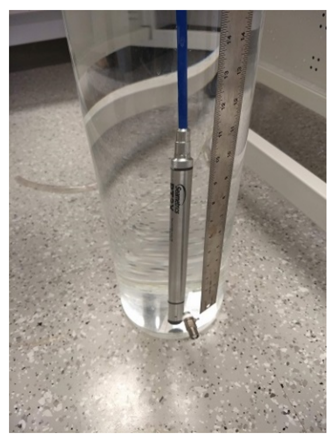

e) Seametrics PT2X Pressure Sensor

Figure 7-8. AC Test Setup.

As shown in the figure, the radar and ultrasonic sensors were fixed in the bracket and leveled in their positions, while the wave height gauge and the pressure sensor were carefully submerged in the water (Figure 7-8d and Figure 7-8e). To reduce the possibility of biasing the results during the measurement process, it was essential to fix the non-contact sensing devices in the horizontal plane and the pressure sensor and wave height gauge in the vertical plane. The measurements were taken separately from the five sensors because the diameter size of the cylinder was not large enough to operate all devices at once. In addition, every test was repeated three times to investigate the accuracy of the data detected by the sensing devices.

7.3.1.2 Experimental Results of AC Test

Results from the AC test revealed that the reviewed sensors were well calibrated and measured the level of pure water with high accuracy. Figure 7-9 shows the recordings logged by the sensing devices during the AC test.

The wave height gauge was not able to measure more than 24 inches of water depth since the gauge length is limited to 2 ft. Therefore, the Akamina AWP-24-SP began to register data when the water level reached 24 inches because the gauge hung down from the head of the cylinder. In addition, the pressure sensor also measured the water depth with great accuracy (Figure 7-9). This finding indicate that this sensors might be suitable for use of submersible sensing devices in water-tight vessels with fairly slow current or filled with stationary water. In the case of the pressure sensor, it was necessary to obtain the specific gravity of the liquid to convert the recorded pressure to the water level. This step would be a drawback if the properties of the liquid in which the device was submerged were unknown. Moreover, technicians reported that the results logged by the pressure sensor were easily disrupted with water movement caused by a water pump installed at the bottom of the acrylic cylinder to drain the water, while non-contact sensors did not react to this movement unless free-surface waves occurred.

Data recorded by the Senix ToughSonic 14 ultrasonic sensor showed less error than the two other non-contact sensing devices. Note that the measurement performance was repeated three times. The sensor recordings clearly showed that the ToughSonic 14 ultrasonic sensor detected the level of pure water in the acrylic cylinder with high accuracy. However, that was not always the case for the FDU91 ultrasonic sensor since an error between the sensor output and the water level was seen when the water level reached 34 inches and 42 inches (Figure 7-9). Additionally, technicians noted a period of latency of about 5 to 6 seconds before the ultrasonic sensor responded to the water-level rise. Nonetheless, the data recorded by the sensor showed that the device was able to measure the level of pure water with a high degree of accuracy. In a similar manner, the radar sensor registered the level of pure water with high accuracy. In fact, data from the two last sets of sensor readings corresponded closely to the level of water in the AC test. However, the results logged by the FMR20 radar sensor showed that there were several errors associated with the first set of recordings. The cause of these errors during the first reading are unclear, yet the possibility that the radar sensor was not leveled appropriately in the first set of measurements cannot be ruled out. Because the non-contact sensing devices—ultrasonic and radar sensors—measure the distance from the water surface, defining a reference datum regarding the level of water rise is essential.

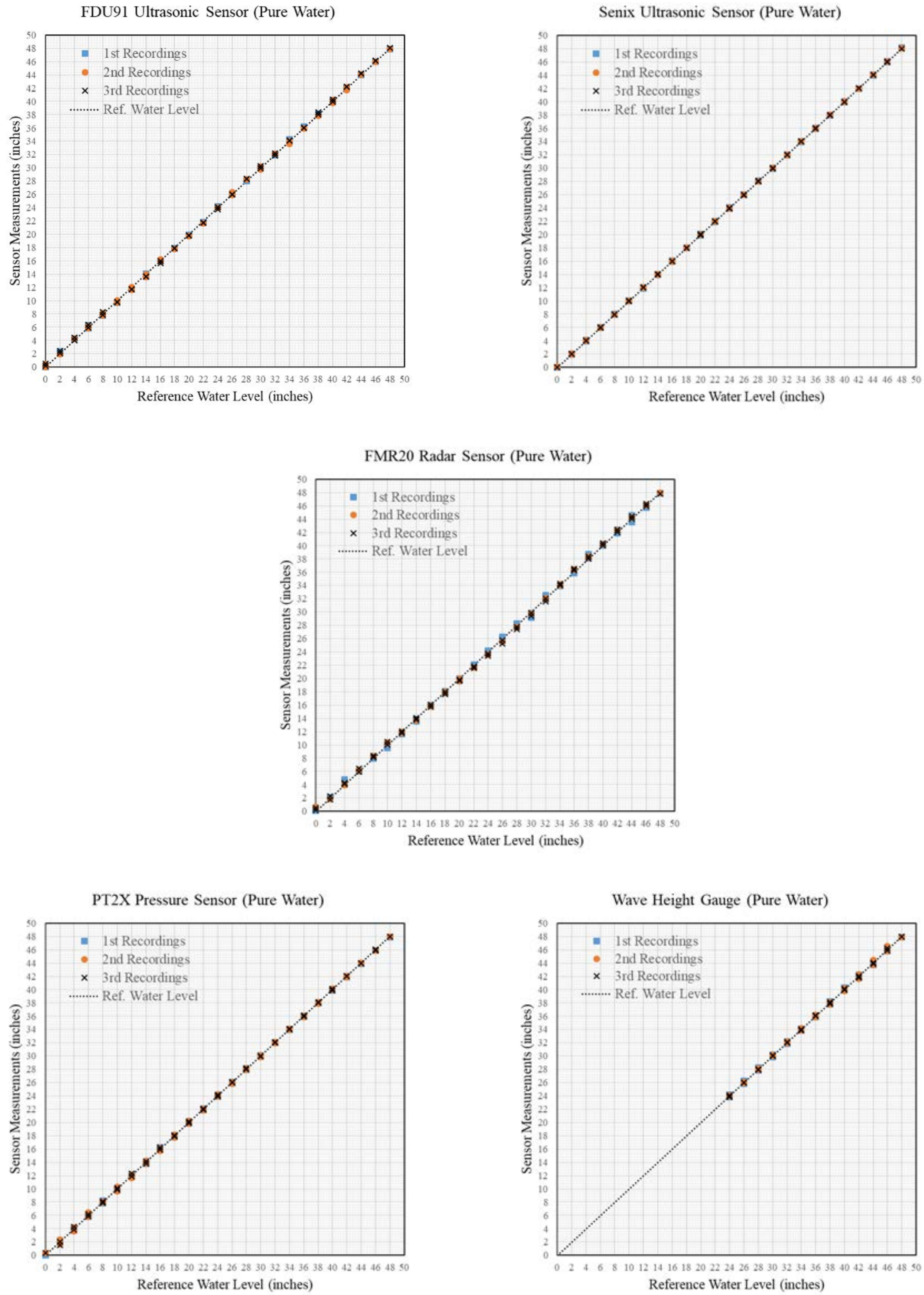


Figure 7-9. Sensor Output from AC Test.

Finally, all sensors proposed in Task 6 passed the AC test. In fact, Figure 7-9 illustrates that the sensors were able to sense the level of pure water in water-tight vessels with relatively high precision. Properties such as hysteresis and repeatability of sensor measurements are discussed in more detail in Section 7.4, and the diagrams in Figure 7-9 are useful for examining these properties as well. As shown in the figure, no distinguishable errors were seen between the sensor output and the water depth to indicate a long-term stability issue with sensor measurements. In addition, Figure 7-9 shows that the maximum hysteresis of the sensor output was small. In fact, that was the case for all sensors tested in the AC test since the maximum hysteresis of the recorded measurements was less than 5 percent.

7.3.2 Water Tank Test

The researchers decided to perform WT tests with pure water under stagnant and turbulent conditions for three sets of recordings since the main goal of Task 6 was to assess the capability of the sensors to estimate the level of water rise in both pure and polluted water. The test steps needed to be conducted in four different environmental conditions to evaluate the robustness of the sensing devices in hot and cold weather, as well as dry and humid environments. The WT test then had to be repeated once more with foam and debris to identify the accuracy, precision, and long-term stability of the measurements reported by the flood sensors.

7.3.2.1 Experimental Setup of WT Test

Figure 7-10 portrays a schematic view of the setup and equipment required for the WT test. As shown in Figure 7-10, a 125-gallon plastic water storage tank was located at an elevation of 38 inches to act as a water reservoir, while a bucket 3 ft in diameter and depth was placed on the floor. As in the AC test, a wood frame was used to hold the non-contact devices. A rugged staff gauge was used so the technicians could visually measure the level of water. In addition to the staff gauge, a $^{1}/_{6}$-hp submersible water pump was used to control the volume of water throughout every set of data recordings. The water pump was placed in the bucket to push water back to the upper reservoir.

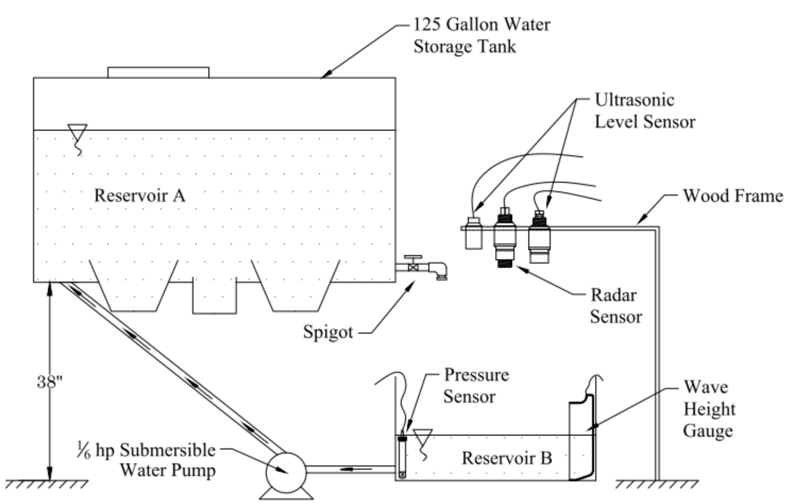


Figure 7-10. Schematic View of Setup Prepared in Sensor Lab for WT Test.

7.3.2.2 Experimental Procedure of WT Test

The experimental approach developed for the AC test was also employed in the WT test. However, the measurements were recorded at only three elevations: 6 inches, 12 inches, and 18 inches. The technicians logged the water-level data from five sensors for every 6 inches of water rise. After finishing the measurements, the technicians recorded the new data as the water pump removed almost 30 and 60 gallons of water from the bucket to the reservoir. In other words, the backward evaluation took place for 6 inches and 12 inches of water depth. To assess the accuracy of the data detected by the sensors, the procedure described above was completed in a set of three periods. The process of data collection was completed using all five sensors simultaneously. Consequently, this process allowed a comparison to be made between the capabilities of each sensor in determining the water level when they are employed under identical conditions. After the first set was completed at room temperature, the procedure was repeated in turbulence to examine the ability of the sensors to capture the height of sloshing waves. The testing procedure was then performed in stagnant water to assess the ability of the sensors to identify the water level with foam and debris present (see Figure 7-11 and Figure 7-12).

Figure 7-11. Foam in Bucket.

Figure 7-12. Debris in Bucket.

As the final step of the WT test, the researchers moved the setup shown in Figure 7-10 into heating chambers located at the Texas A&M University System RELLIS Campus. At this point, the ambient state of chambers was selected so that the performance of flood sensors could be evaluated in different environmental conditions, namely low, medium, and high temperature, as well as medium and high humidity. Five sensors measured the water level concurrently, similar to the procedure that was followed in the sensor lab except for the environmental conditions, which were not kept constant during the test. The chamber temperature used for the primary environmental test was set at 35°F in a dry condition, and the following test was completed in a different chamber where the temperature was set at 104°F in a dry condition. The temperature was then controlled at 68°F, and the humidity was increased to 50 percent in the third chamber and to 100 percent in the fourth chamber. The measurements were taken at three elevations similar to what was completed in the sensor lab.

Figure 7-13 through Figure 7-16 show the experimental procedure followed in the WT test. As can be seen in Figure 7-13, the reservoir was elevated to more than 3 ft because the researchers intended to benefit from the gravitational force, which facilitates the water transfer between the water tank and the bucket. The $^{1}/_{6}$-hp submersible water pump was placed in the bucket so that the technicians were able to move the water from the bucket to the reservoir without causing sloshing waves. The water pump was temporarily elevated to the liquid surface at the onset of turbulent conditions to study the negative consequences of wavy water on the sensors' reading. Figure 7-14 shows the position of sensors while measuring the surface elevation of the water. The ultrasonic sensors and the radar sensor were fixed at the top of the bucket, as shown in Figure 7-15, while the wave height gauge and the pressure sensor were submerged in the water, as shown in Figure 7-16. As in the AC test, the ultrasonic and radar sensors were fixed in the horizontal plane, and the two other sensors were attached to the edge of the bucket so that they were submersed in the water vertically.

Figure 7-13. Reservoir Positions.

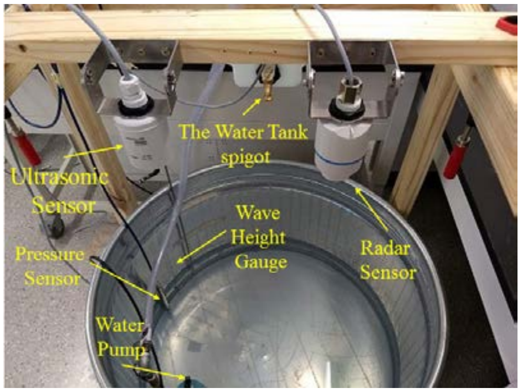


Figure 7-14. Measurement Process in Bucket.

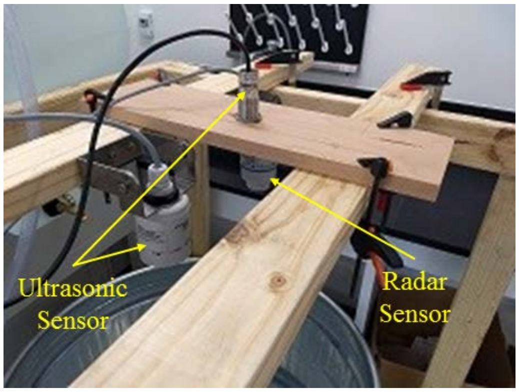


Figure 7-15. Non-contact Devices.

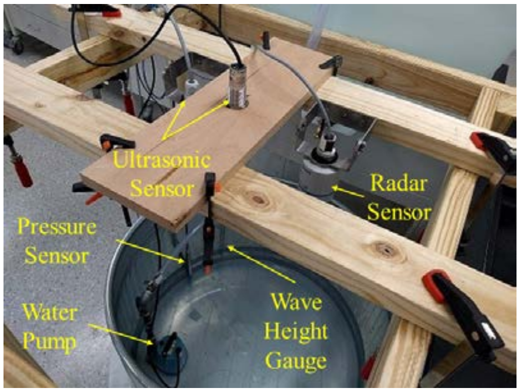


Figure 7-16. Device Placement in Relation to Bucket.

7.3.2.3 Experimental Results of WT Test

Figure 7-17 to Figure 7-24 show measurements of the water level from the WT test reported by the evaluated sensors. The intention of this evaluation was to assess the ability of the sensing devices to identify the water depth in different local conditions. Review of these figures reveals a correlation between the sensor output and real data, except for in a few cases where the test was performed with debris and foam. Figure 7-17 shows the sensor recordings from the WT test with pure water. As shown in the figure, sensors detected the water level with great accuracy, yet some errors were seen in records reported by the FDU91 ultrasonic sensor when the level of water was at 12 inches, not only in stagnant water but also in the turbulent condition (see Figure 7-18). In fact, no changes in the water level were reported by the sensor for static and dynamic conditions. The Senix ToughSonic 14 ultrasonic sensor detected the water height with high accuracy, similar to the AC test. Figure 7-18 demonstrates the sensor output where the water surface was turbulent. A comparison between the measurements recorded by the sensors revealed that the Senix ToughSonic 14 still detected the sloshing waves with higher accuracy than the other sensors. This finding might indicate a high sensitivity of the sensor to detect the level of pure water at room temperature in both stagnant and turbulent conditions. The FMR20 radar sensor was not able to measure the height of waves precisely, particularly when the level of water reached 6 inches. Regarding submersible sensing devices, the PT2X pressure sensor also measured sloshing waves with good accuracy. However, some errors were observed in the results registered by the Akamina AWP-24-SP wave gauge.

Some degree of uncertainty was associated with sensor recordings due to an accumulation of debris or foam on the water surface. For example, the non-contact devices did not measure the water level precisely when debris was released in the water (see Figure 7-19). As an example, the FMR20 radar sensor poorly detected the level of water in this case. While three sets of recordings were planned in the WT test, the researchers concluded that the measurements logged by the Senix ToughSonic 14 ultrasonic sensor corresponded to the water level most times, but not always, even though the sensor had measured the level of pure water perfectly before. In fact, it was expected that the non-contact sensors would fail to estimate the water depth when the measurement process was performed with debris because some portions of the waves sent from the device are reflected away and never return. Among these non-contact devices, the FDU91 ultrasonic sensor measured the water level better than the other two sensors. In addition, the submersible devices generally measured the water level with greater accuracy than the non-contact sensors.

Figure 7-20 includes diagrams plotted based on the sensor output from the WT test with foam. The PT2X pressure sensor detected the water depth precisely. In addition, the FDU91 ultrasonic sensor measured the water level even better than it did in the WT test with debris. The Senix ToughSonic 14 ultrasonic sensor failed to detect the level of water with foam. The device frequently showed warning signs during the test that implied undetermined water level. However, the ability of the sensor to detect the water surface was evaluated under extreme conditions of giant bubbles, which rarely occur in flooding conditions. After the foam became more stable with a uniform thickness and medium-size bubbles, the third attempt of recordings with the Senix ToughSonic 14 ultrasonic sensor measured the level of water with reasonable accuracy. Therefore, the researchers concluded that the size of bubbles and the foam thickness can profoundly affect the sensor reading; in fact, the FMR20 radar sensor and the Akamina AWP-24-SP wave gauge also failed to precisely detect the level of water with foam, as shown in Figure 7-20.

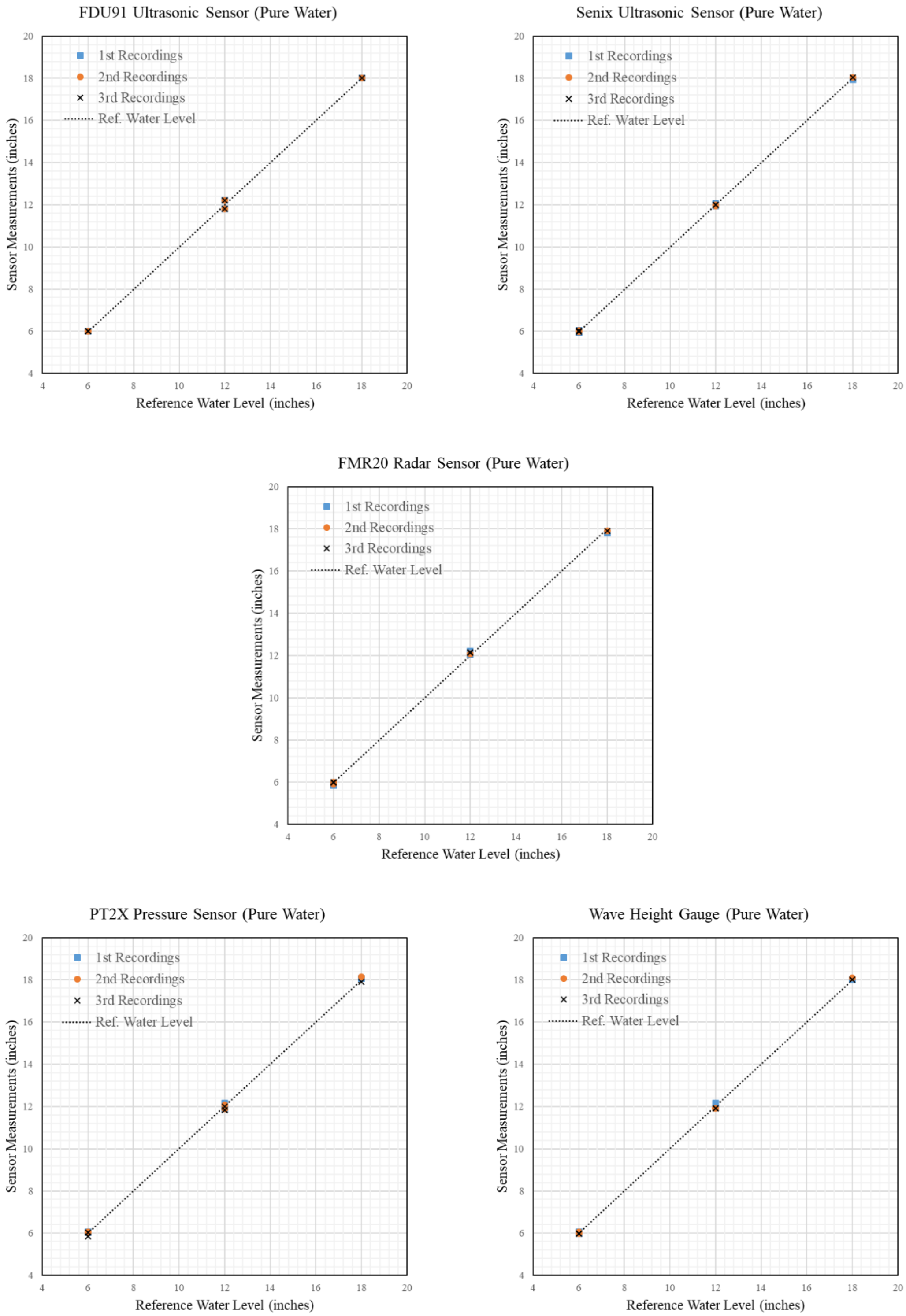


Figure 7-17. Sensor Output from WT Test with Pure Water.

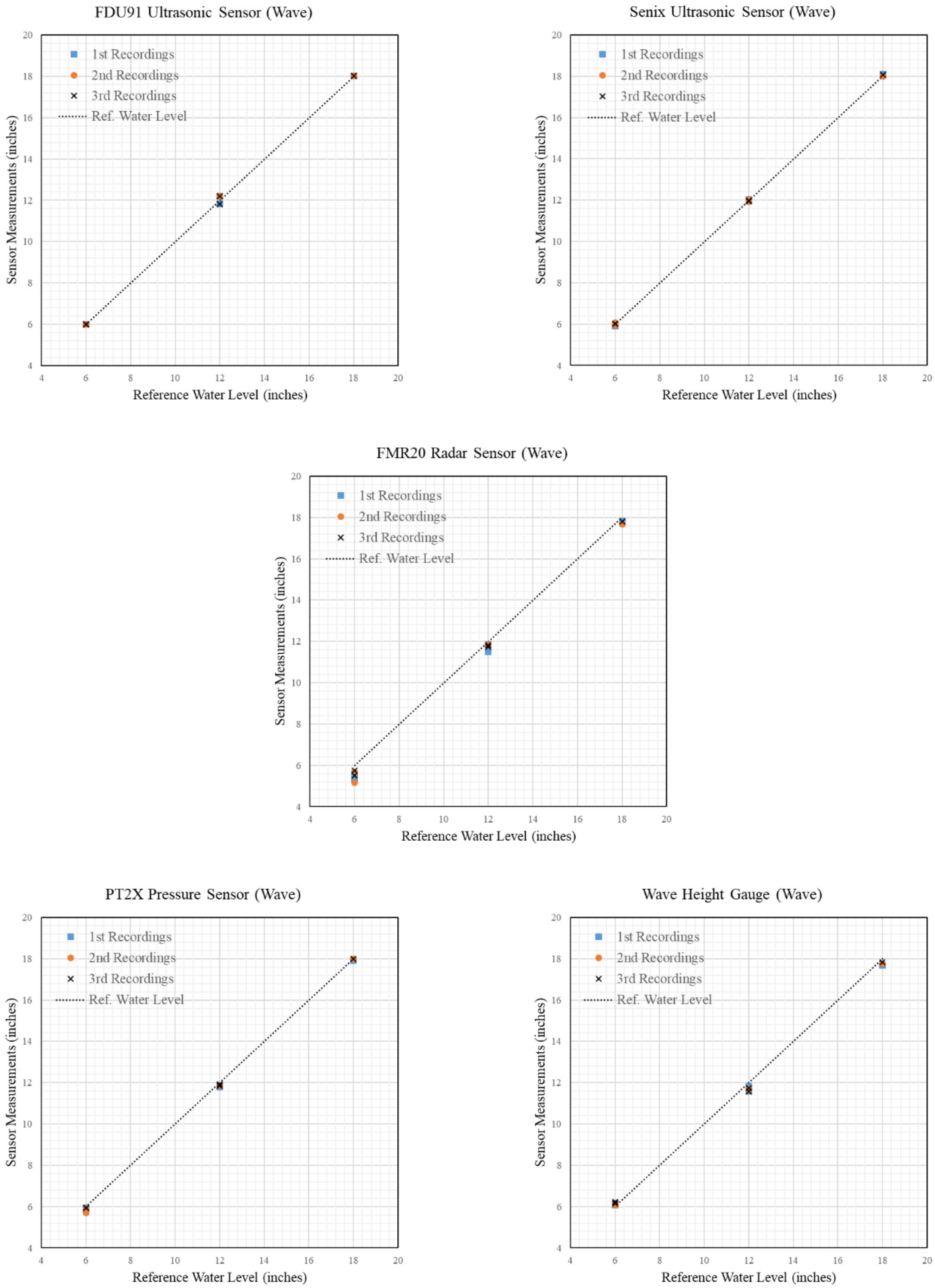


Figure 7-18. Sensor Output from WT Test with Turbulent Flow.

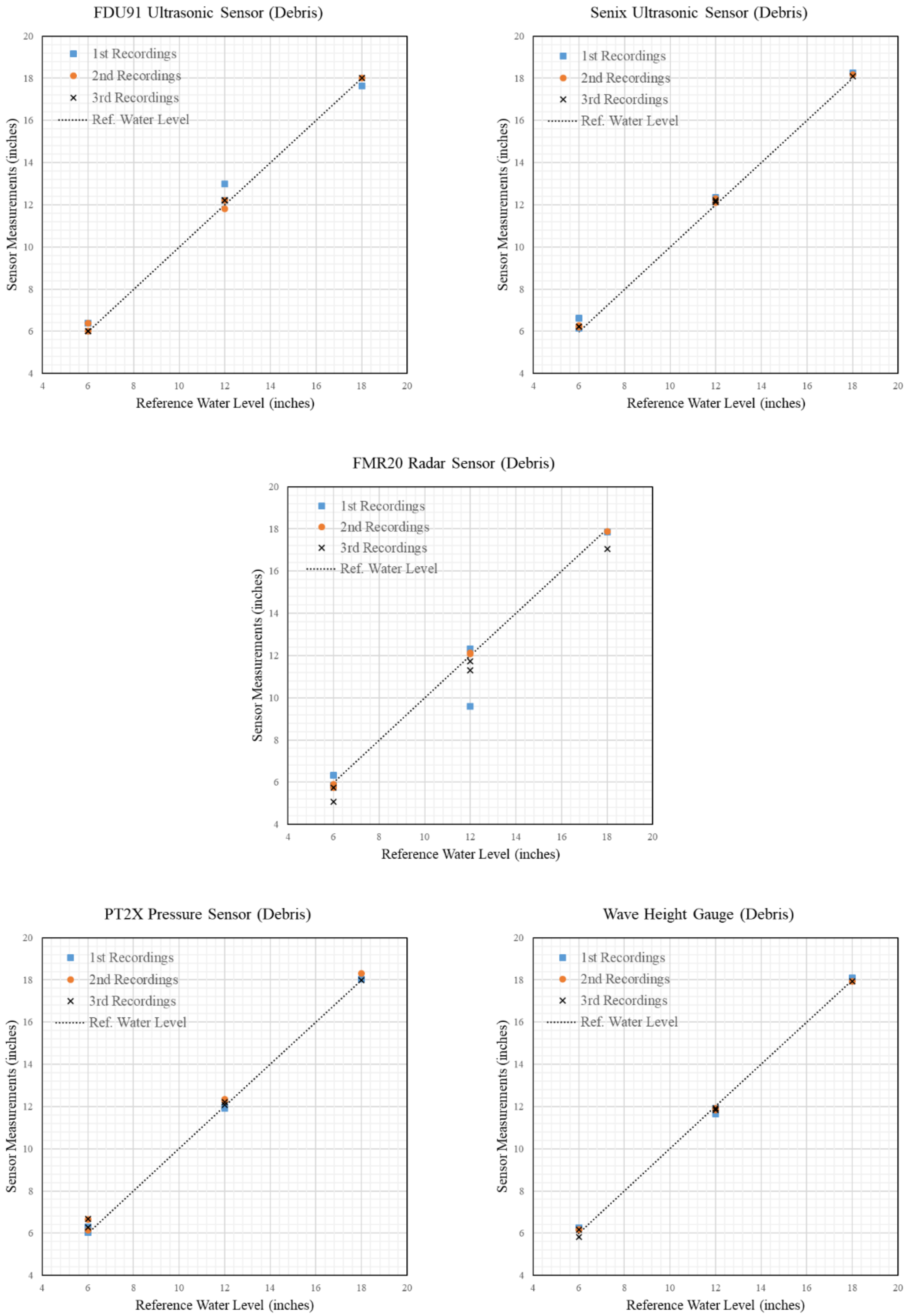


Figure 7-19. Sensor Output from WT Test with Debris.

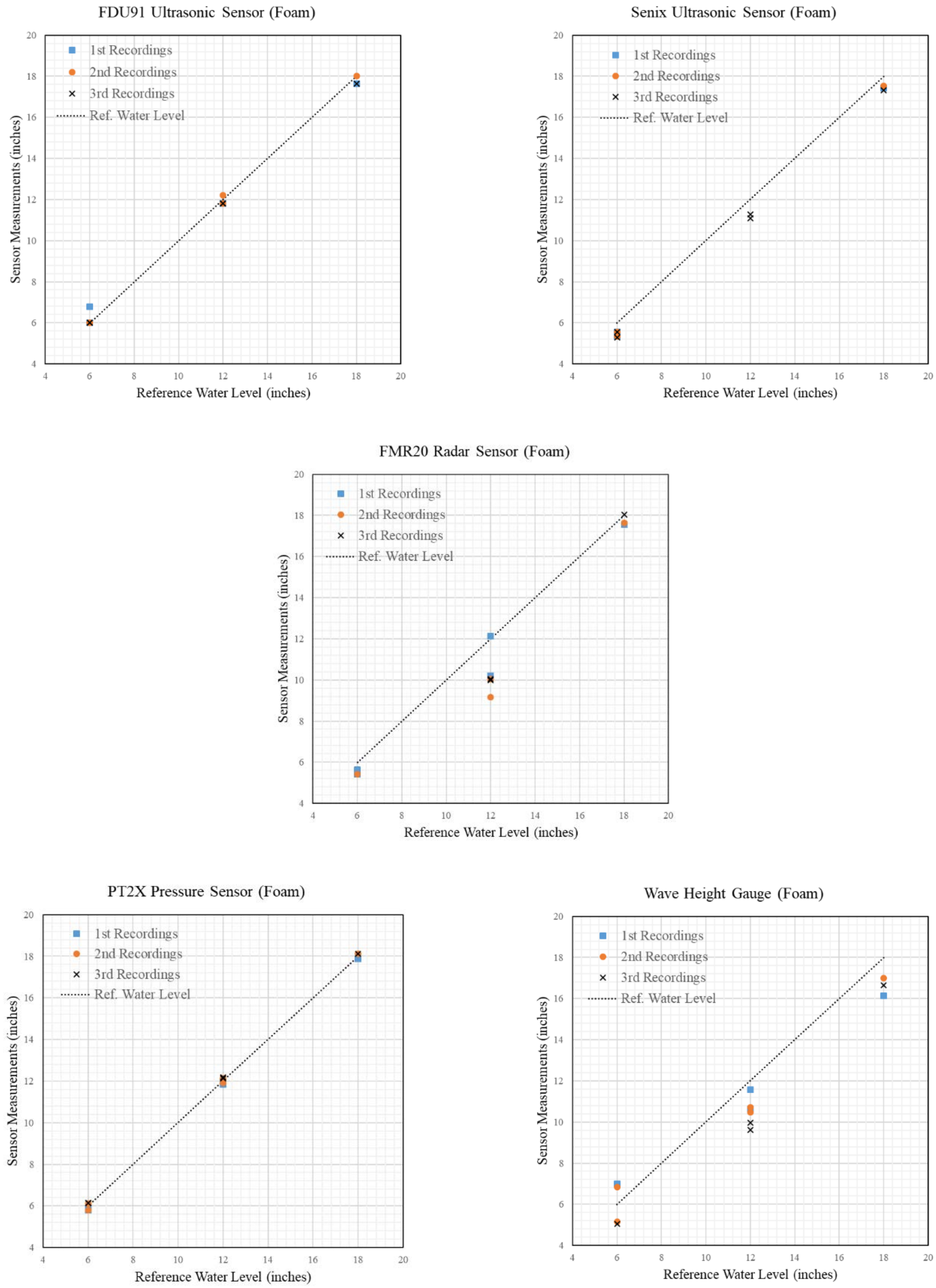


Figure 7-20. Sensor Output from WT Test with Foam.

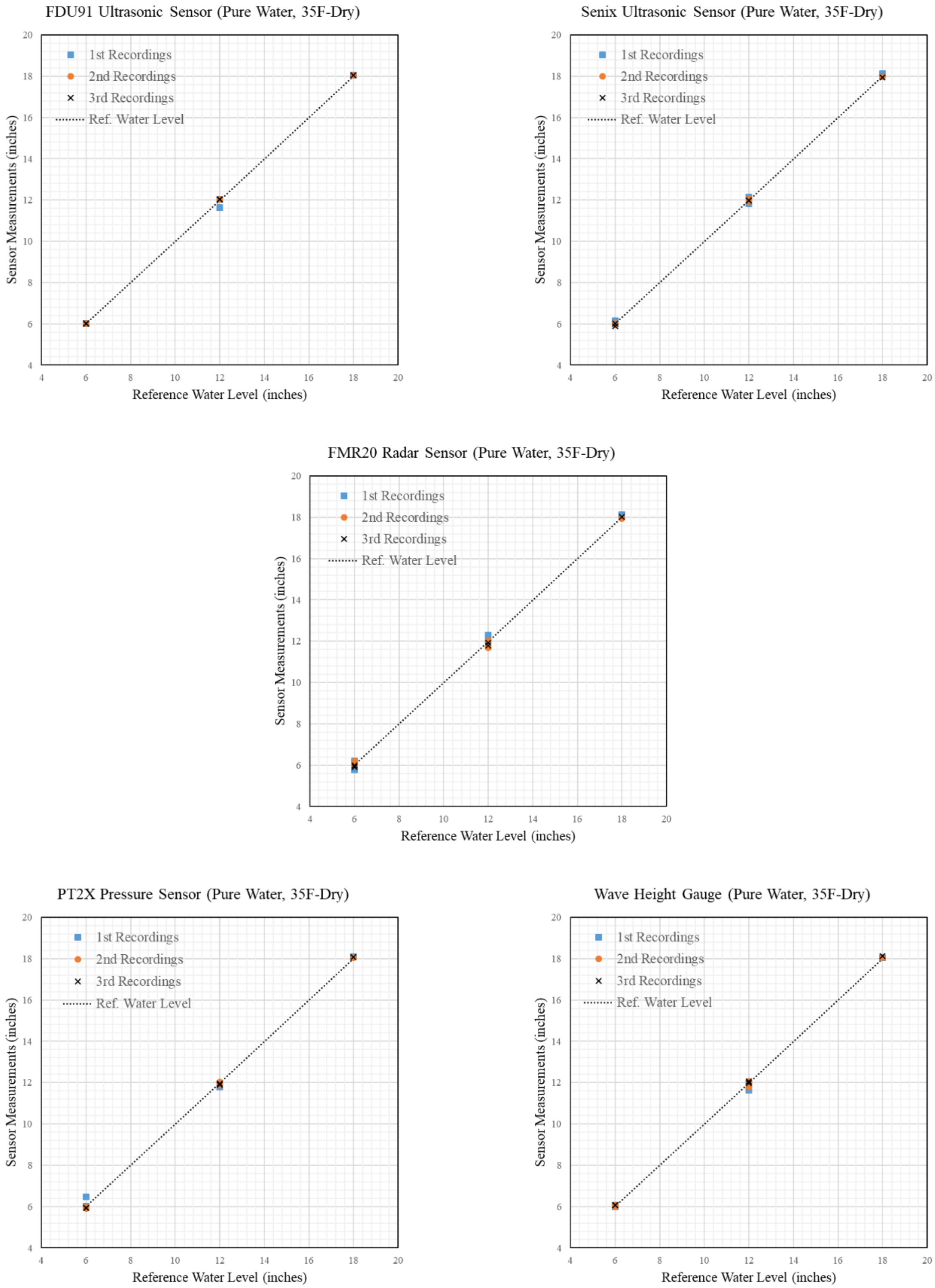


Figure 7-21. Sensor Output from WT Test with Pure Water under 35°F and Dry Condition.

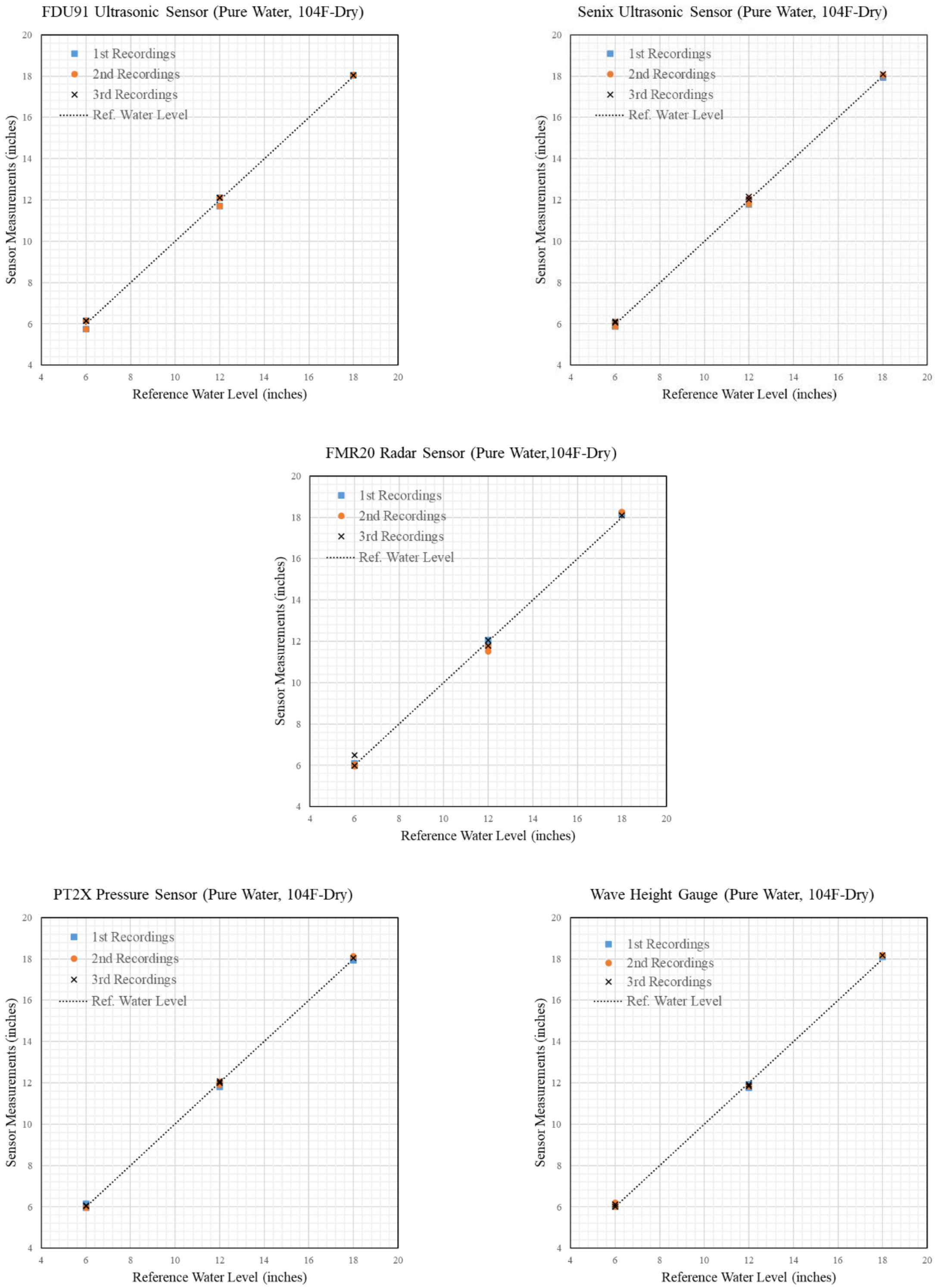


Figure 7-22. Sensor Output from WT Test with Pure Water under 104°F and Dry Condition.

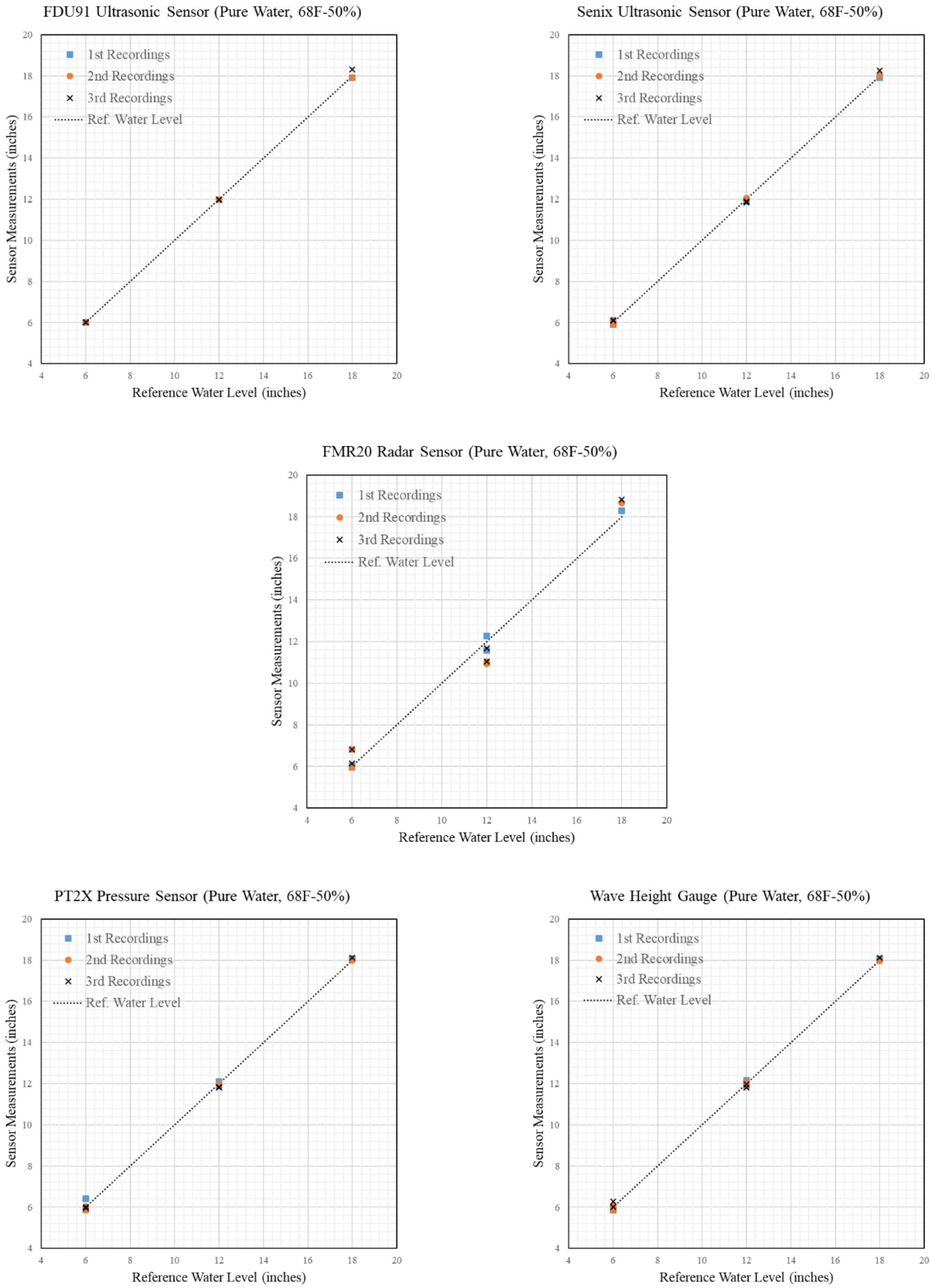


Figure 7-23. Sensor Output from WT Test with Pure Water under 68°F and 50% Humidity.

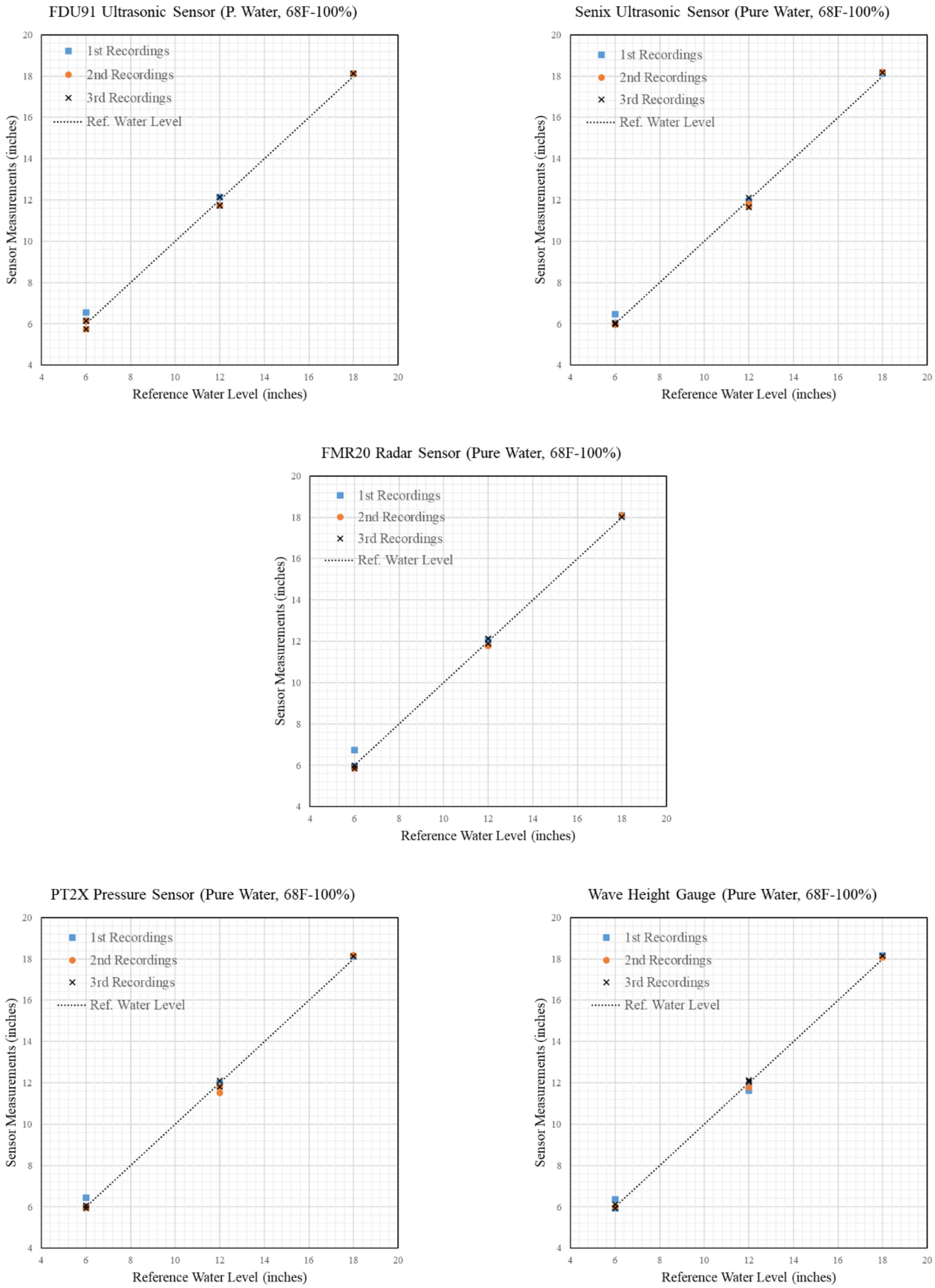


Figure 7-24. Sensor Output from WT Test with Pure Water under 68°F and 100% Humidity.

The penultimate evaluation of sensor performance in different local conditions was determined according to tests conducted at room temperature. However, the results obtained from these tests are not reliable references to assess the efficiency of sensing devices in different environmental conditions. Figure 7-21 through Figure 7-24 show sensor output from the WT test performed in four different chambers. Four dissimilar conditions were considered to determine the sensing ability of the devices in a very cold and hot temperature, as well as the dry and wet states. In this regard, Figure 7-21 shows sensor measurements under 35°F and dry condition, whereas Figure 7-22 shows sensor recordings under 104°F and no humidity. As can be seen in these figures, the sensors were able to detect the level of pure water with reasonable accuracy. A comparison between sensor recordings under low and high temperatures revealed that the accuracy of the results reported by submersible sensors was higher than that registered by ultrasonic sensors if the temperature was relatively high, and vice versa. The Senix ToughSonic 14 ultrasonic sensor detected the water level with reasonable accuracy in both states. Meanwhile, the FMR20 radar sensor reported the water level slightly less accurately than the other sensors in both cold and hot environments. Figure 7-23 and Figure 7-24 show the sensor output from the WT test under 68°F and 50 percent and 100 percent humidity, respectively. Almost all sensors evaluated were able to determine the level of pure water in the wet condition with high accuracy, except the FMR20 radar sensor. However, by increasing the humidity in Chamber 4, the sensing ability of the radar sensor became better. Finally, a comparison between the results plotted in Figure 7-21 and Figure 7-24 showed that the ultrasonic sensors generally measured the level of water in wet conditions with slightly better accuracy than the submersible sensing devices.

Therefore, the researchers concluded that the sensors were able to detect the level of pure water in either stagnant or turbulent conditions with high accuracy. Nevertheless, the researchers observed that the FDU91 ultrasonic sensor was not as fast as the other sensors in determining the height of sloshes. The device did have better performance compared to other non-contact sensing devises during the WT test with foam and debris. On the other hand, the Senix ToughSonic 14 ultrasonic sensor failed in determining the level of water with extreme foam and had some errors with the measurements observed during the WT test with debris. However, the sensor performance in the other cases predicted in the WT test was quite superior to the other sensing devices. Both ultrasonic sensors measured the level of pure water in different environmental conditions with high accuracy. This accuracy indicates that the ultrasonic sensors can measure a target elevation in wet conditions with better accuracy than the other sensors. The PT2X pressure sensor performed reasonably during the WT test. Although the sensor was able to measure the water level in any condition predicted during the test with high precision, the accuracy of measurements recorded by the Seametrics PT2X declined slightly when the humidity increased. The FMR20 radar sensor was able to detect the distance between the water surface and the device with good accuracy, yet the sensor failed to precisely measure the water level when the WT test was performed with foam and debris, similar to the Senix ToughSonic 14 ultrasonic sensor. In addition, the sensor did not perform well when the humidity was 50 percent, but accuracy of the measurements increased when the humidity was either increased to 100 percent or decreased to 0 percent. It is not clear why the radar sensor measured data with some errors in the wet condition with 50 percent humidity. The Akamina AWP-24-SP, like the non-contact sensing devices, was not able to exactly determine the level of water with foam, but the wave gauge did predict the water depth in the other cases with reasonable accuracy.

7.3.3 Field Test

The final phase of the experimental performance assessed in Task 6 was to evaluate the ability of the sensors to detect the water level in flooding conditions. The researchers conducted an experiment in the test facility constructed for the purpose of flood simulation in Task 5.

7.3.3.1 Experimental Setup of Field Test

Figure 7-25 shows the tanker used to spill 4,866 gallons of water into a ditch 15.25 ft wide and 42 ft long. The ditch is a recess trench whose depth reaches 42 inches in places. A wood frame was anchored to the trench wall to hold the sensing devices during the measurement process. In addition, two flat-bottomed rails weighed down the wood frame to avoid any instability of recordings due to the water-level rise. Figure 7-25 to Figure 7-28 show the position of sensors used in the field test. Note that the same devices that measured the water level in the two previous tests were also used in the field test.

Figure 7-25. Facility Test.

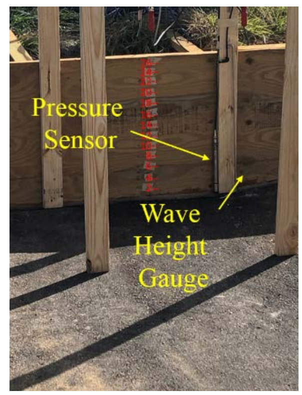


Figure 7-26. Wave Height Gauge and Pressure Sensor.

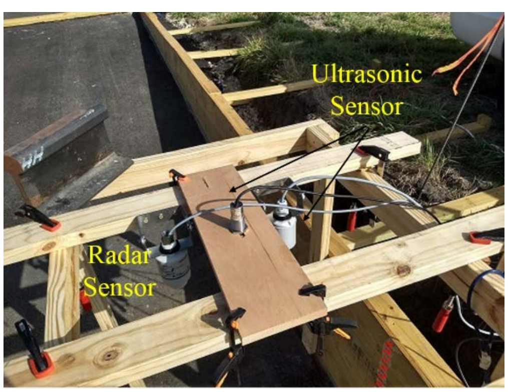


Figure 7-27. Non-contact Sensing Devices.

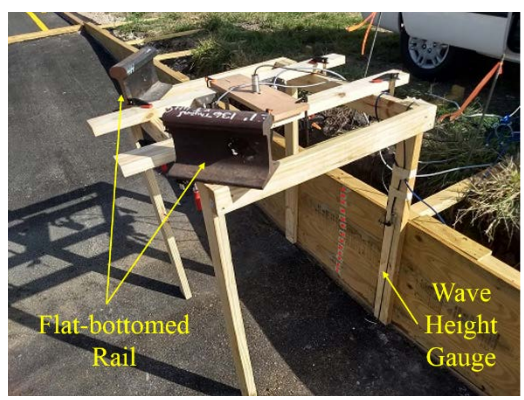


Figure 7-28. Test Setup.

7.3.3.2 Experimental Procedure of Field Test

After attaching sensors to the wood frame, one technician was equipped with a computer and communication devices, while another controlled the volume of water spilling into the trench from the tanker, as shown in Figure 7-29. The technicians recorded the sensor output for every 2 inches of the water-level rise. Thus, the procedure followed for the field test was somewhat similar to the AC test, except that the recording was completed in one set period. In other words, the backward evaluation test was eliminated in the field test because the goal was to investigate whether the sensing devices were able to detect the water level in flooding conditions. Figure 7-30 shows the sensors during the measuring process when the water level was at 6 inches, which would cause floating vehicles. Figure 7-31 demonstrates the same performance at the end of the experiment where the water depth was 22.76 inches. This level of water can result in floating trucks and severe damage to small cars.

Figure 7-29. Filling Up Trench with Water.

Figure 7-30. Measuring Water Level at 6 inches.

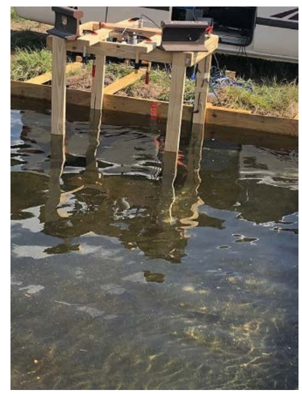


Figure 7-31. Measuring Water Level at 22.76 inches.

7.3.3.3 Experimental Results of Field Test

Figure 7-32 shows the sensor measurements from the field test under 86°F and 85 percent humidity. As shown in the figure, the evaluated sensors detected the water level with fair accuracy. Nevertheless, some errors were observed in recordings reported by sensors where the water level was less than 8 inches. Although these errors were negligible, the cause of the small deviation is not clear, yet the effect of wind should be considered as a reason for such errors. The Akamina AWP-24-SP wave height gauge detected the water level, including less than 8 inches, with good accuracy.

From the results plotted in Figure 7-32, the researchers concluded that both the non-contact and submersible sensing devices detected the level of pure water at almost the same accuracy. However, the ultrasonic sensors were able to measure the level of water with slightly better accuracy than the submersible devices when the humidity increased to over 50 percent. This observation was also noted during the WT test in Chamber 3 and Chamber 4.

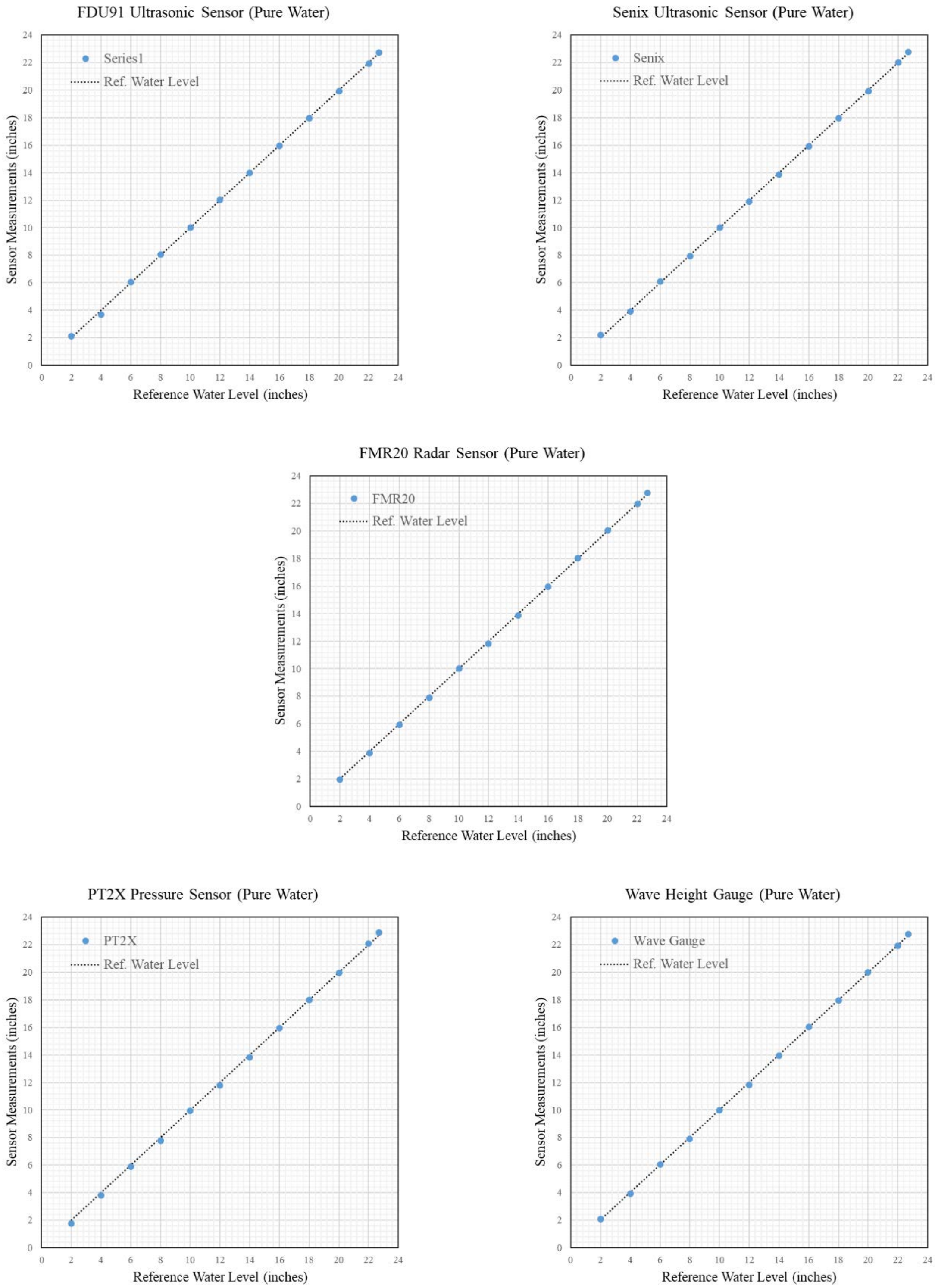


Figure 7-32. Sensor Output from Field Test with Pure Water under 86°F and 85% Humidity.

Figure 7-33 shows a comparison between sensor recordings in the turbulent condition. Sloshing waves were created by shaking a wood stick in the water after finishing the measurements in the stagnant condition. Three sets of recordings are shown in Figure 7-33 and include the logging data from before the motion began on the water surface, at the moment that the waves appeared on the water surface, and after the water became stationary (labeled in Figure 7-33 as stagnant water, sloshing water, and after sloshing water). Furthermore, the slosh height reached to a quarter-inch from mean elevation, 22.76 inches of the water level in the stagnant condition. This elevation was considered as a reference level to study the effect of sloshing waves on sensor efficiency.

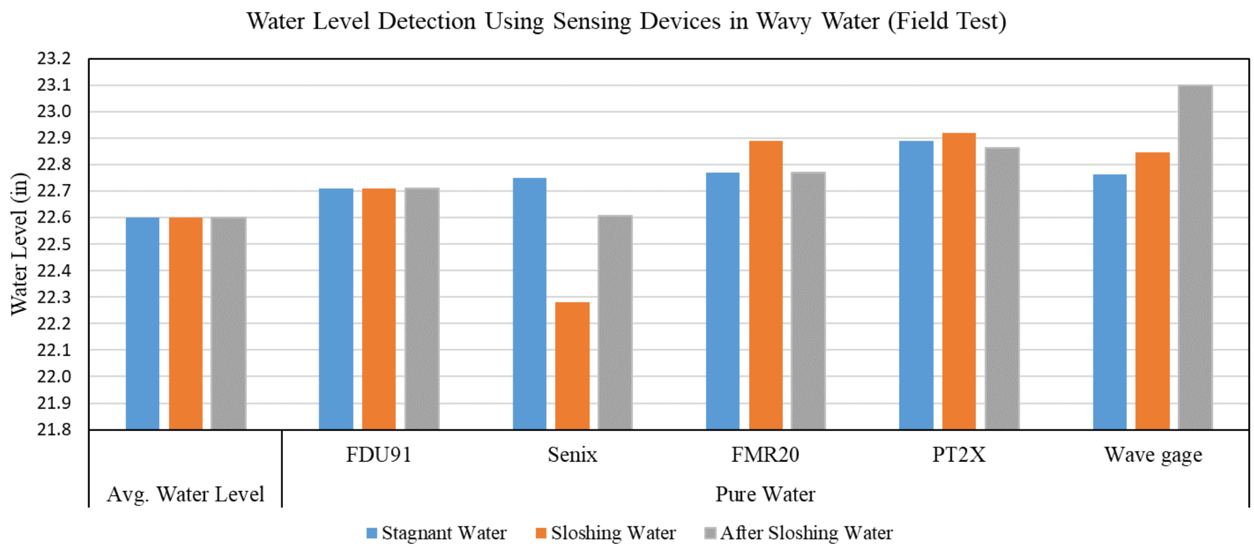


Figure 7-33. Comparison between Sensor Recordings in the Turbulent Condition.

As can be seen in Figure 7-33, the FDU91 ultrasonic sensor reported the height of sloshes the same as it registered the water level in the stagnant condition, which indicates that the sensor is less sensitive to wavy conditions. This disadvantage of the FDU91 was also observed earlier in the WT test. The Senix ToughSonic 14 ultrasonic sensor showed good accuracy to detect the water level in the three different local conditions. This finding confirms that the Senix ToughSonic 14 can detect motion in shallow water with high accuracy. Similarly, the FMR20 radar sensor and the PT2X pressure sensor sensed the height of sloshing waves, yet the accuracy of the measurements was not as precise as those reported by the Senix ToughSonic 14 ultrasonic sensor. However, this was not the case for the measurements recorded by the Akamina AWP-24-SP wave height gauge. The device reported the water depth with a large deviation from the actual data, more specifically after sloshing resided.

7.4 EVALUATION

To ensure the measurement accuracy of each of the flood sensors described in the preceding sections, evaluation of the efficiency of flood sensors in roadways was essential. The sensing devices should not be assumed ideal, meaning the measurement error reported by the sensors was plausible. In fact, the objective of Task 6 was to investigate if the error was relatively small and could possibly be negligible; otherwise, the conditions making the sensor measurements inaccurate needed to be identified.

Because the measurement accuracy of flood sensors is a concern, evaluation of nonlinearity, hysteresis, and repeatability of the device output is common since most manufacturers assess the accuracy of their products based on these properties (*77*). Other factors, such as ambient conditions, may also be considered because such parameters influence the efficiency of these devices. The experimental tests described in Section 7.3 were developed to analyze the aforementioned factors to rank the sensors based on their applicability, robustness, accuracy, durability, precision, and repeatability.

The term nonlinearity can be expressed by determining the linearity errors of the sensor output. These errors more often represent a very small deviation from the actual elevation. A possible means of checking nonlinearity of sensor measurements is to determine R-squared (R^2) values. This method can be a practical tool to obtain errors that are too small and are not distinguishable. For example, consider a range set of data registered by a sensor; in this case, R^2 is defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (e_i)^2}{\sum\limits_{i=1}^{n} (y_i - \mu)^2} \qquad (7.1)$$

where e refers to the error between the measured and actual data, n is a sample size of the dataset, and μ represents the mean of the sample. In the case where R^2 is equal to 1, one can conclude that the dataset is linearly distributed. In contrast, if R^2 is less than 1, then the dataset is assumed to be non-linearly distributed. The previous statement can also be defined in terms of the sensor calibration, meaning a sensing device should be properly calibrated if the average of R^2 values calculated from the sensor output is fairly close to 1.

Figure 7-34 demonstrates the linearity of the measurements recorded by sensors in all three tests with pure water. The linearity of recordings reported by a unique sensor deviates slightly from one test to another. However, the error is so small that it can be concluded that well-calibrated sensors were used during the experimental phase in Task 6. In this regard, almost the same R^2 values of the measurements were logged by the sensing devices from the field test, which modeled a flooding condition, as seen in Figure 7-34.

In addition to device calibration, R^2 values can be studied to investigate the accuracy of the measurements from the sensing devices compared with the actual data. For example, the Senix ToughSonic 14 ultrasonic sensor generally detected the water level with better accuracy than the other sensors. No error was seen on recordings reported by the ultrasonic sensor in the AC test, and a very small error was observed on the device measurements in the WT test. In addition, the bar diagram in Figure 7-34 reveals that the pressure sensor, like the ultrasonic sensor, measured the level of pure water with slightly better accuracy than the other sensors.

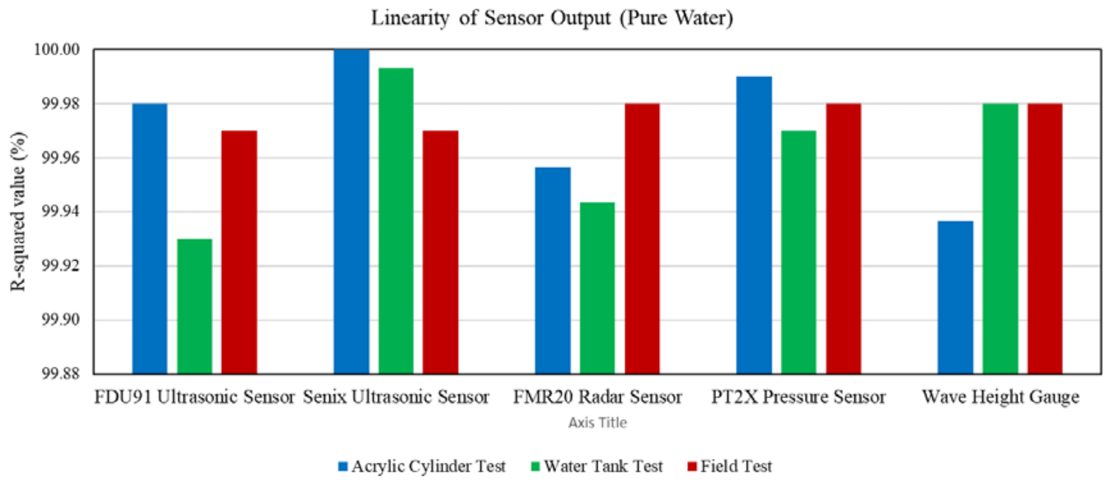


Figure 7-34. R^2 Values Showing Linearity of Sensor Output.

Figure 7-35 represents R^2 values based on the sensor output from the WT test. These values provided a better understanding of nonlinearity measurements reported by the evaluated sensors on eight different local and environmental conditions. As mentioned before, the Senix ToughSonic 14 ultrasonic sensor failed to detect the level of water with foam, which is illustrated by the low R^2 value for the measurements reported by the ultrasonic sensor in Figure 7-35. In fact, this number represents only one of three attempts during the measuring process since the device signaled an error during the two first tries. Low R^2 values were also observed in the measurements recorded by the wave gauge and the FMR20 radar sensor. In the case of the radar sensor, some nonlinearity in data was seen under 68°F and 50 percent humidity. Additionally, the measurement accuracy reduced when the FMR20 radar sensor and Senix ToughSonic 14 ultrasonic sensor were used to determine the level of water with debris. Aside from these cases, Figure 7-35 shows high linearity in most cases between device output and an actual elevation of water, which indicates a reasonable correlation between the sensor reading and the reference water level.

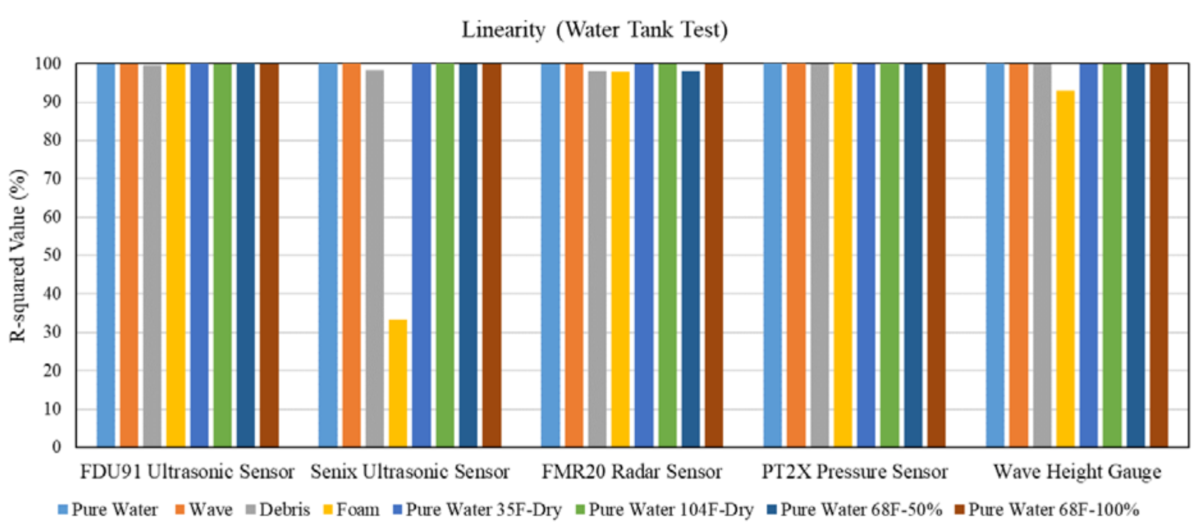


Figure 7-35. R^2 Values Showing Linearity of Sensor Output, WT Test.

Another aspect to examine when analyzing the accuracy of the sensor recordings is the hysteresis error. Hysteresis occurs when there are a couple of dissimilar measurements reported for a certain input without changing the local conditions. To determine whether the errors are associated with sensor measurements, calculating the maximum hysteresis is common. The intention behind the calculation of the maximum hysteresis is to determine the largest possible error that may occur during the measurement process. The error is expressed in terms of the maximum deviation of sensor measurements compared with the actual values. Eq. (7.2) gives the maximum hysteresis, $\psi_{\max}$:

$$\psi_{\max} = \frac{\max\left|y_i^u - y_i^l\right|}{y_{\max} - y_{\min}}, \quad i = 1, 2, 3, ..., n \tag{7.2}$$

where y^u and y^l are the upper and lower values of sensor measurements for a specific input. Additionally, y_{max} and y_{min} are the optimum values in a dataset. Because $\psi_{\max}$ represents the maximum deviation of sensor observations for a certain elevation, if the maximum error approaches zero, then it can be assumed that the device measured the target elevation with high precision, and vice versa. Figure 7-36 shows the average maximum hysteresis based on sensor measurements from the AC test with pure water. As can be seen in the figure, the maximum error calculated based on recordings logged by the Senix ToughSonic 14 ultrasonic sensor was less than the hysteresis obtained for other sensor measurements. Evidently, the ultrasonic sensor measured the level of pure water with higher precision than the other sensors. In fact, this higher precision was also valid for measurements recorded by the FDU91 ultrasonic sensor, where the maximum hysteresis associated with the sensor output was slightly greater than the one reported for the Senix ToughSonic 14 ultrasonic sensor. In contrast, the average maximum hysteresis obtained based on the results reported by the wave height gauge was more than the ones computed for the other sensors. This result means the Akamina AWP-24-SP wave height gauge reported the water depth with less precision compared to the other devices. Another submersible sensing device proposed in Task 6 measured the level of pure water with good precision—in fact, better than the FMR20 radar sensor. This result indicates that the radar sensor did not measure the water level with good precision like the other non-contact devices did.

Figure 7-37 demonstrates $\psi_{\max}$ calculated based on sensor measurements from the WT test in eight different conditions. Figure 7-37 provides a better understanding of device measurements to investigate whether the results were accurate. As expected, the maximum hysteresis obtained based on recordings from the Senix ToughSonic 14 ultrasonic sensor was generally less than errors associated with other sensors, except when the WT test was performed with foam. In the case with foam, the maximum hysteresis intensified up to almost 45 percent, which implies lack of precision in measurements reported by the sensor. In contrast, the FDU91 ultrasonic sensor measured the water level in each of the eight conditions with reasonable precision.

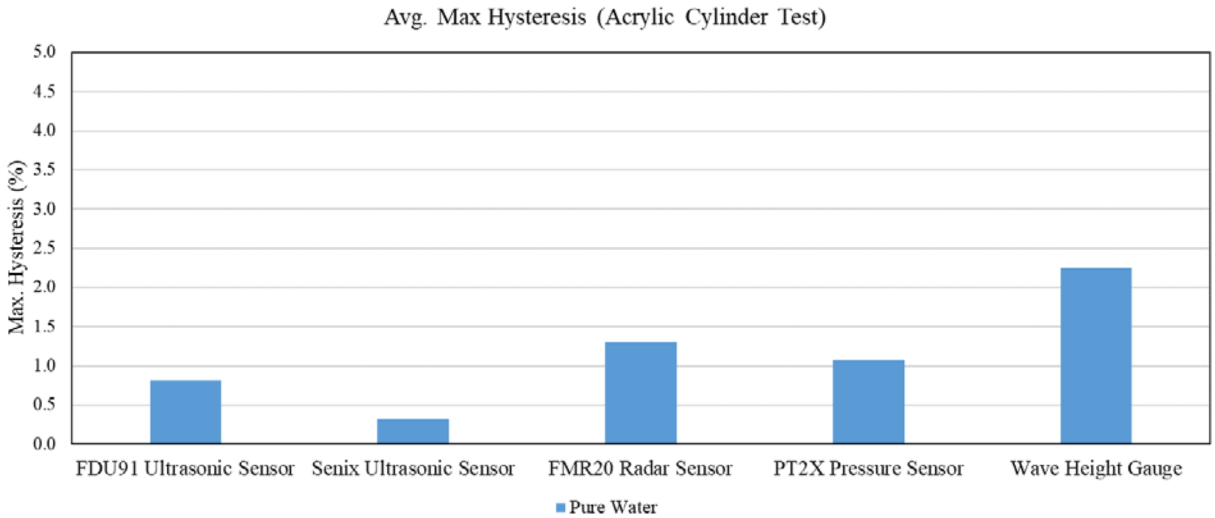


Figure 7-36. Average Maximum Hysteresis of Sensor Output, AC Test.

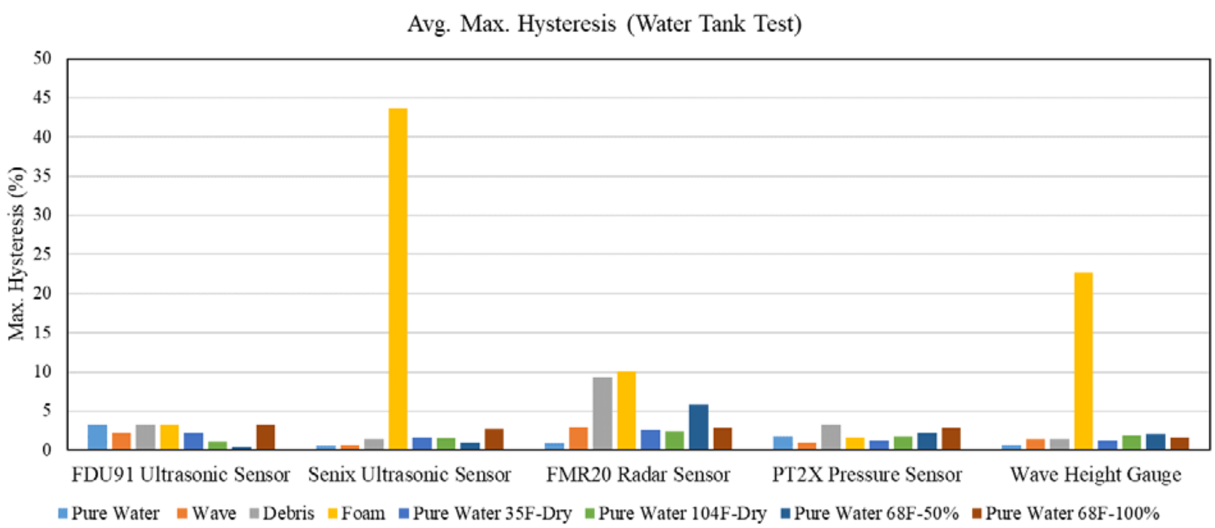


Figure 7-37. Average Maximum Hysteresis Error of Sensor Output, WT Test.

The maximum hysteresis calculated based on the data reported by the FMR20 radar sensor showed less precision compared to the errors computed from the other sensors. Even if one ignores the results obtained based on the WT test with foam and debris, the radar sensor did not measure the level of pure water in four different environmental conditions with any great precision compared with results computed for the other sensors. In contrast, the PT2X pressure sensor was able to sense the water depth more precisely compared to the other sensors. However, Figure 7-37 shows that the precision declined when the temperature and the humidity increased when the pressure sensor was used for water-level detection. This observation was noted in the accuracy of the measurements registered by the pressure sensor in dry and wet conditions. The wave height gauge was also able to detect the water depth with acceptable precision except when the test was conducted with foam.

Repeatability is an error showing the ability of a sensor to identify the water level on a frequent basis. While studying the nonlinearity of a dataset provides the criterion to obtain the sensor calibration, and the maximum hysteresis error shows the precision of measurements logged by a sensing device, repeatability gives the standard to assess the long-term stability of the sensor recordings. Excellent repeatability gives high accuracy in results, yet devices that can measure data with great precision are typically expensive. On the other hand, poor repeatability is not a positive sign for a flood sensor and causes a lack of trust in future measurements. Thus, the selection of a sensing device appears to be a cumbersome task because both cost and accuracy must be considered.

Examining the repeatability in terms of pooled standard deviation, σ_p, which itself is a function of standard deviation, σ, of each sample in a dataset is worthwhile.

$$\sigma_p^2 = \frac{\sum_{i=1}^{N} (n_i - 1)\,\sigma_i^2}{\sum_{i=1}^{N} (n_i - 1)}, \quad i = 1, 2, 3, ..., N \tag{7.3}$$

where n is the sample size of a sub-dataset, and N represents a total number of sub-datasets. Note that similar to maximum hysteresis, lower σ_p represents less deviation in a dataset, which implies more stability of the sensor output.

Figure 7-38 shows pooled standard deviations calculated from sensor measurements reported during the AC test. The recordings logged by the Senix ToughSonic 14 ultrasonic sensor were more stable than the data measured by the other sensors. This finding is illustrated in Figure 7-38 via a comparison of the pooled standard deviations obtained for the Senix ToughSonic 14 ultrasonic sensor with the ones registered for the other sensors. The FMR20 radar sensor showed it was not able to report more repeatable data since the pooled standard deviation calculated for this device was more than 20 percent. This was also the case for the FDU91 ultrasonic sensor and the PT2X pressure sensor in that σ_p was computed at about 16 percent. In addition, measurements logged by the wave height gauge represented a considerable error of about 20 percent, which indicates instability in long-term measurements. Therefore, researchers concluded that the Senix ToughSonic 14 ultrasonic sensor was the only device able to report long-term stable data.

Figure 7-39 shows pooled standard deviations based on recordings reported by the flood sensors in the WT test. The PT2X pressure sensor was able to measure data with higher repeatability compared to the other sensors. Nonetheless, ignoring the results based on the WT test with foam, one can argue that the Senix ToughSonic 14 ultrasonic sensor and the Akamina AWP-24-SP registered more stable data similar to the pressure sensor. The pooled standard deviation determined based on the measurements reported by the latter devices during the WT test with foam was more than 100 percent. This finding implies a wide-range distribution of measurements showing the device's failure to sense the surface of the water. The FDU91 ultrasonic sensor recorded data with reasonable repeatability, yet its success in determining the level of water with foam and debris was questionable. Additionally, as seen in Figure 7-39, the ultrasonic sensor was not able to measure stable data when humidity increased to 100 percent, while the Senix ToughSonic 14 ultrasonic sensor measured the water level with better stability in similar environmental conditions. Regarding repeatability, the FMR20 radar sensor reported generally poor results. Analysis of measurements recorded by the non-contact device revealed instability in measured data in the test conducted with foam and debris. In fact, this instability of recordings was also observed when the sensor logged the water level in wet conditions.

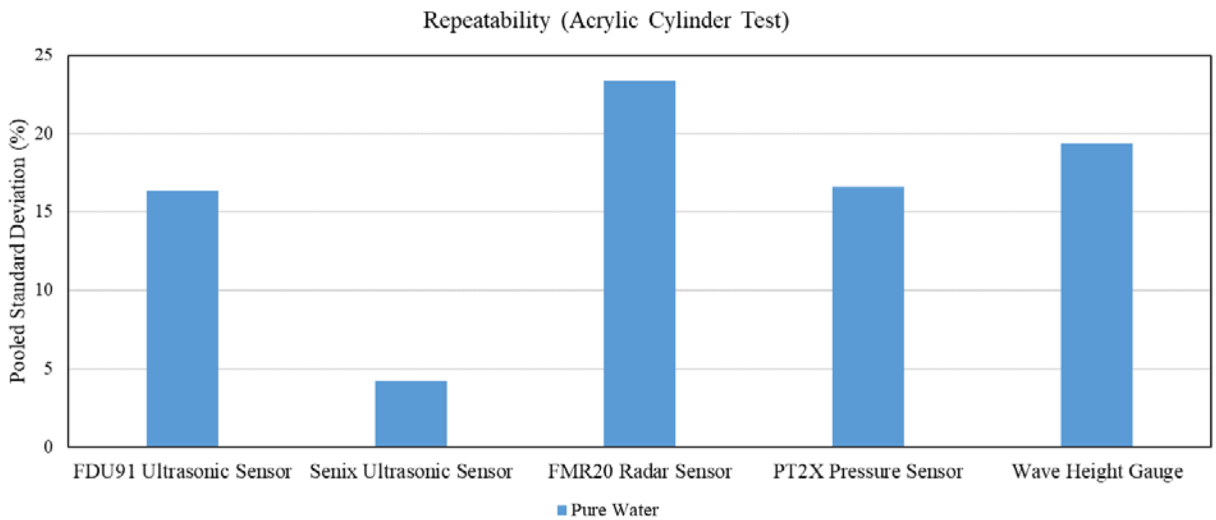


Figure 7-38. Pooled Standard Deviation for Repeatability of Sensor Output, AC Test.

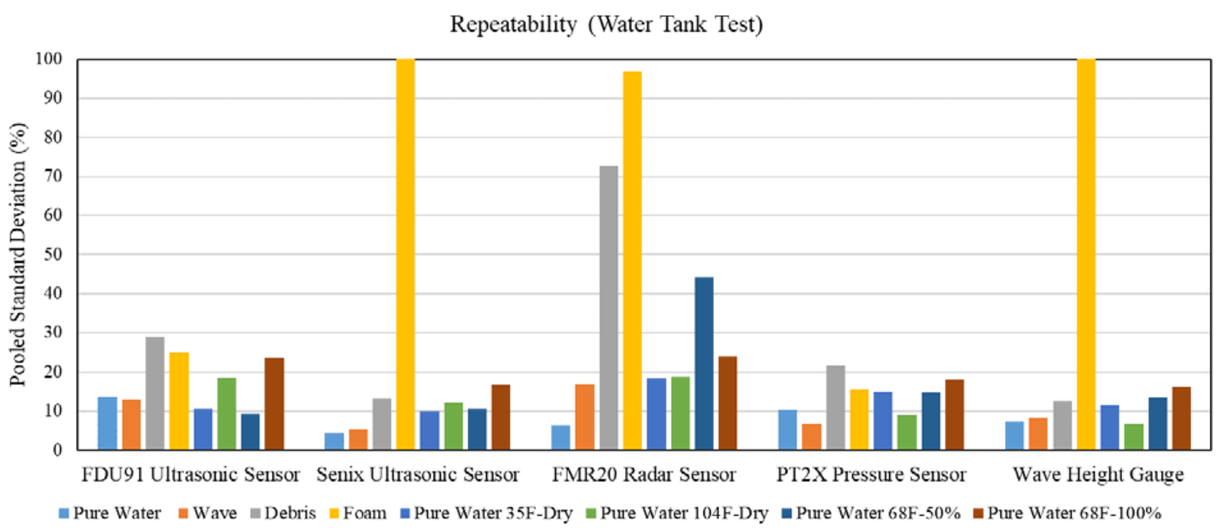


Figure 7-39. Pooled Standard Deviation for Repeatability of Sensor Output, WT Test.

To evaluate flood sensors and their efficiency in flooding conditions, the researchers defined a set of standards based on the properties discussed earlier. These properties included applicability, robustness, and durability of sensing devices used on the roadways, in addition to accuracy, precision, and repeatability of recordings reported by the sensors. The last three properties had already been studied in detail and could be determined based on sensor measurements from the AC test, meaning the R^2 values reported above were used to grade the ability of the sensors to detect the level of pure water with accuracy, while maximum hysteresis, $\psi_{\max}$, was used to determine whether the device measured the target elevation with precision or not, and pooled standard deviations, σ_p, were used to verify if a sensor was able to report long-term stable data. Moreover, the results obtained from the WT test were used to obtain robustness of the sensors because the test was conducted in a variety of local conditions (e.g., tested with foam and debris, in laminar and turbulent water flow, and in different environmental states, such as cold and hot temperatures and dry and wet conditions).

Another factor used to assess the efficiency of the flood sensors was their long-term durability. Durability is defined based on the probability that a device may be damaged in the future. Here, two sets of defects were predicted: cable and wire damages, and sludge- and dirt-related destruction. These damages are seen more with submersible devices (e.g., dirt can block the water inlet in the pressure sensor and impact the measurement process). Applicability of sensors was the other factor considered in Task 6 to evaluate the efficiency of sensing devices. Some sensors cannot be used in an industrial environment because they are chemically resistant. The sensors should also be corrosion resistant, particularly submersible devices since they are constantly submerged in water. Moreover, some limitations regarding the applicability of a sensing device exist. Power demand and maximum range of measurements exemplify such restrictions that make the utilization of sensing devices in the field questionable.

In addition to the properties discussed above, two other factors influenced the ranking system shown in Table 7-2: (a) the simplicity of installing sensors and the amount of equipment required to support the device, and (b) the cost, including the device itself and its accessories. Some sensors required peripheral equipment for which power would be needed. The latter is also included in Table 7-2 under the ease-of-use column.

Table 7-3 summarizes the evaluation metric of the flood sensors proposed in Task 6. According to the results reported in Table 7-3, non-contact sensing devices are overall superior to submersible sensors. Before commissioning the experimental phase, the researchers predicted that all sensors would perform well enough to determine the level of pure water with high accuracy and precision. However, the FMR20 radar sensor would not register data with long-term stability compared to the other sensors. The sensor is simpler to use on site without the FDU91 ultrasonic sensor. The Senix ToughSonic 14 ultrasonic sensor appears to be the most reliable sensor tested in Task 6. Its reasonable cost and good applicability for use on the roadways make the sensor more efficient than the other sensors. The PT2X pressure sensor can measure the level of water in any condition with high accuracy, as shown in Table 7-3. However, concern for the durability of the sensor arose when sludge and dirt were mixed in the water. In addition, the installation of submersible sensors is not as easy as non-contact devices. Moreover, the Akamina AWP-24-SP wave height gauge is limited to 2-ft measurements of the water level, which raises the question of whether the device is appropriate to use in areas with flooding conditions. The wave gauge system installation also requires a larger number of accessories than the other sensors tested.

Table 7-2. Table of Specifications.

Score	Applicability			Robustness			Durability	Accuracy	Precision	Repeatability	Ease of Use			Cost
	%			%			%	%	%	%	%			$
				Different Conditions				Pure Water						
	Chemical Resistance	Power Demand	Max Range	Linearity	Max Hysteresis	Repeatability	Local damage	Linearity	Max Hysteresis	Repeatability	No. of Equipment Required Power	Sensor Installation	No. of Accessories	Sensors & Accessories
weight	0.33	0.33	0.33	0.33	0.33	0.33	1	1	1	1	0.33	0.33	0.33	1
0 (worst)	Submersible Non-Chemical Res. Non-Corrosion Res.	>220V	<2ft	0–10	>25	100	Cable/ Sludge & Dirt	0–10	>25	100	>10	Contact	>3	>3k
1	Submersible Chemical Res. Non-Corrosion Res.			10–20	22.5–25	90–100		10–20	22.5–25	90–100	9			2.7k–3k
2	Submersible Non-Chemical Res. Corrosion Res.	<220V		20–30	20–22.5	80–90		20–30	20–22.5	80–90	8			2.4k–2.7k
3	Submersible Chemical Res. Corrosion Res.		2ft–6ft	30–40	17.5–20	70–80	No Cable/ Sludge & Dirt	30–40	17.5–20	70–80	7			2.1k–2.4k
4	Non-Contact Non-Chemical Res. Non-Corrosion Res.	<110V		40–50	15–17.5	60–70		40–50	15–17.5	60–70	6		2	1.8k–2.1k
5				50–60	12.5–15	50–60		50–60	12.5–15	50–60	5			1.5k–1.8k
6	Non-Contact Chemical Res. Non-Corrosion Res.	<60V	6ft–12ft	60–70	10–12.5	40–50	Cable/ No Sludge & Dirt	60–70	10–12.5	40–50	4			1.2k–1.5k
7				70–80	7.5–10	30–40		70–80	7.5–10	30–40	3			0.9k–1.2k
8	Non-Contact Non-Chemical Res. Corrosion Res.	Battery	12ft–18ft	80–90	5–7.5	20–30		80–90	5–7.5	20–30	2		1	0.6k–0.9k
9				90–100	2.5–5	10–20		90–100	2.5–5	10–20	1			0.3k–0.6k
10 (best)	Non-Contact Chemical Res. Corrosion Res.	0	>18ft	100	0–2.5	0–10	No Cable/ No Sludge & Dirt	100	0–2.5	0–10	0	Non-Contact		0.0k–0.3k

Table 7-3. Evaluation Metric for Evaluating Flood Sensor Technologies.

	Applicability	Robustness	Durability	Accuracy	Precision	Repeatability	Ease of Use	Cost	Rating
Weighting Factor in %	20	10	10	10	10	10	20	10	Out of 10
Ultrasonic Sensor: Endress & Hauser FDU91	6.8	9.1	10.0	9.0	10.0	9.0	9.3	3.0	8.24
Ultrasonic Sensor: Senix ToughSonic 14	8.0	7.7	10.0	9.0	10.0	10.0	7.8	9.0	8.74
Radar Sensor: Endress & Hauser FMR20	7.5	7.5	10.0	9.0	10.0	8.0	9.0	7.0	8.45
Pressure Sensor: Seametrics PT2X	5.3	9.3	3.0	9.0	10.0	9.0	6.0	6.0	6.89
Wave Gauge: Akamina AWP-24-SP	3.7	8.2	3.0	9.0	10.0	9.0	2.8	7.0	5.92

7.5 WARNING DEVICES

The purpose of flood warning systems is to inform drivers of potential danger in flooded areas so that they avoid crossing shallow water and minimize the negative impact of the flood event. There are two different types of flood warning systems, namely passive and active systems, which are discussed in the following sections.

7.5.1 Passive Warning System

Passive warning systems indicate that a location on the road may flood temporarily during a flood or permanently.

7.5.1.1 Temporary Signs and Barricades

Figure 7-40 shows examples of temporary signs and barricades that are conventional ways to warn drivers against crossing a flooded road. Since signs and barricades should be placed at required locations when needed, this system requires agency resources that could be overburdened during emergencies (*66*).

7.5.1.2 Standing Signs

The TxMUTCD provides a series of signs that can be used on roadways that are subject to frequent flooding, as shown in Figure 7-41. This warning system is low in cost for installation and maintenance but has low accuracy.

Figure 7-40. TxDOT Road Closure Signs.

W8-18 W8-18aT W8-18bT

Figure 7-41. TxDOT Flood-Related Weather Condition Signs.

7.5.2 Active Warning System

The active warning system uses a water-level-measuring sensor to detect when a crossing is flood. The system can also have a gate that is mechanically or manually deployed by an operator. The fundamental active warning system consists of:

- Water-level sensor.
- Data logging/recording equipment.
- Power supply.
- Data transmission.
- Housing.
- Warning device.

Based on the need for extra functionality, additional components can be added, such as gates, barrier arms, flashing lights, or others.

7.5.2.1 BlinkerSign LED

TAPCO developed an FRWS, BlinkerSign LED. The system uses an adjustable water-height probe to detect floodwater. The probe cannot measure water level and can be damaged by dirty water, even though the device is in a housing (*80*).

7.5.2.2 Flood Warning Gate

Figure 7-42 shows the flood warning electronic gate system installed by Houston's Street and Drainage Division. The flood warning gate is paired with a web-based system called Flood Information Graphical System to display a flooded road map, to share flood data online, and to inform and navigate emergency vehicles through flooded streets. However, the system has proven to be high in cost and difficult to maintain.

Figure 7-42. Flood Warning Gate Installed in Houston.

7.5.2.3 Automated Gate at Flood-Prone Crossing

Figure 7-43 shows an automated railroad-style gate that closes a road if sensors detect high water levels. Since this system is not connected to the internet, the condition of the system cannot be quickly checked. Also, the look of the system may cause drivers to confuse it with a railroad crossing.

Figure 7-43. Automated Gate at Flood-Prone Crossing.

7.6 CONCLUSIONS

Task 6 involved an experimental study of flood sensors and warning devices to ascertain their ability to measure the water level in flooding conditions and LWCs. Five sensors, including both non-contact and submersible devices, were tested under dissimilar local and environmental conditions. The observations from this experimental work are summarized below.

- The Senix ToughSonic 14 ultrasonic sensor performed very well during the experimental tests. The sensor can measure the water level in different environments, although the device failed to detect the level of water with extreme foam. Some errors were also observed when debris was released into the water. The sensor is not only the most applicable device tested in Task 6 but is also a low-cost device.
- The Endress & Hauser FMR20 radar sensor can predict the level of pure water with good accuracy, yet its performance in measuring the water depth in wet conditions is not as good as the other devices. Like the Senix ToughSonic 14 ultrasonic, some errors were observed in the device measurements when tests were conducted with foam and debris. However, the reasonable cost and the ease of use on site may compensate for this lack of robustness.
- The Endress & Hauser FDU91 ultrasonic sensor is the most expensive device tested in Task 6. The device measured the water level with great accuracy. In addition to two other non-contact devices, the sensor performed well in all cases predicted in Task 6. Moreover, the device reported consistent measurements even with sloshing waves.
- The Seametrics PT2X pressure sensor registered the most accurate results in any condition. The sensor measured up to 11 ft, and the cost is still acceptable. Nonetheless, concerns about installation and durability with minimal maintenance were observed.

- The Akamina AWP-24-SP wave height gauge was also able to predict the water depth with great accuracy but failed to determine the level of water with extreme foam, similar to the Senix ToughSonic 14 ultrasonic and the FMR20 radar sensors. In addition, durability is questionable since the device needs a cover to support the submersible cables and probes. Moreover, the amount of required equipment to support the wave gauge during the measurement process is more than that of the other devices, and power would need to be provided for the equipment. Finally, limitations associated with the sensing device include the sensor not being able to measure more than 2 ft of water depth.

Chapter 8. DEVELOPMENT OF PROTOTYPE CONNECTED VEHICLE FLOOD WARNING SYSTEM

8.1 INTRODUCTION

The objective of Task 7 was to design, build, and test a prototype system for providing alerts and warnings at LWCs using CV technology. In this task, the researchers examined the application of appropriate I2V and I2I technologies for providing flood condition reports at LWCs in a CV environment. The researchers considered two different architectures: one integrated with TxDOT's LoneStar Traffic Management System software and another designed as a standalone system for deployment at an isolated LWC. The researchers followed standard systems engineering principles to perform the following:

- Develop new use cases for providing CV alerts at LWCs.
- Develop the system architecture and system requirements for installing and integrating with flood-monitoring equipment with TxDOT's LoneStar Traffic Management System software.
- Develop interfaces for integrating flood-monitoring sensors with roadside unit (RSU) devices.
- Develop logic for using basic safety messages (BSMs) to trigger alerts to traffic management centers (TMCs) of vehicles entering flooded crossings.
- Develop CV message sets for providing traveler alerts at low water and flood-prone crossings.
- Develop a prototype interface for displaying alerts and warnings of flooded conditions to CVs.
- Develop interfaces and logic for activating external communication devices (such as dynamic message signs [DMSs], flasher assemblies, etc.) to alert travelers to flooded road conditions.

The purpose of this chapter is to summarize system engineering activities associated with the development of the Connected Vehicle Flood Warning System (CV FWS). The researchers also developed prototype applications for use in the proof-of-concept testing in Task 8.

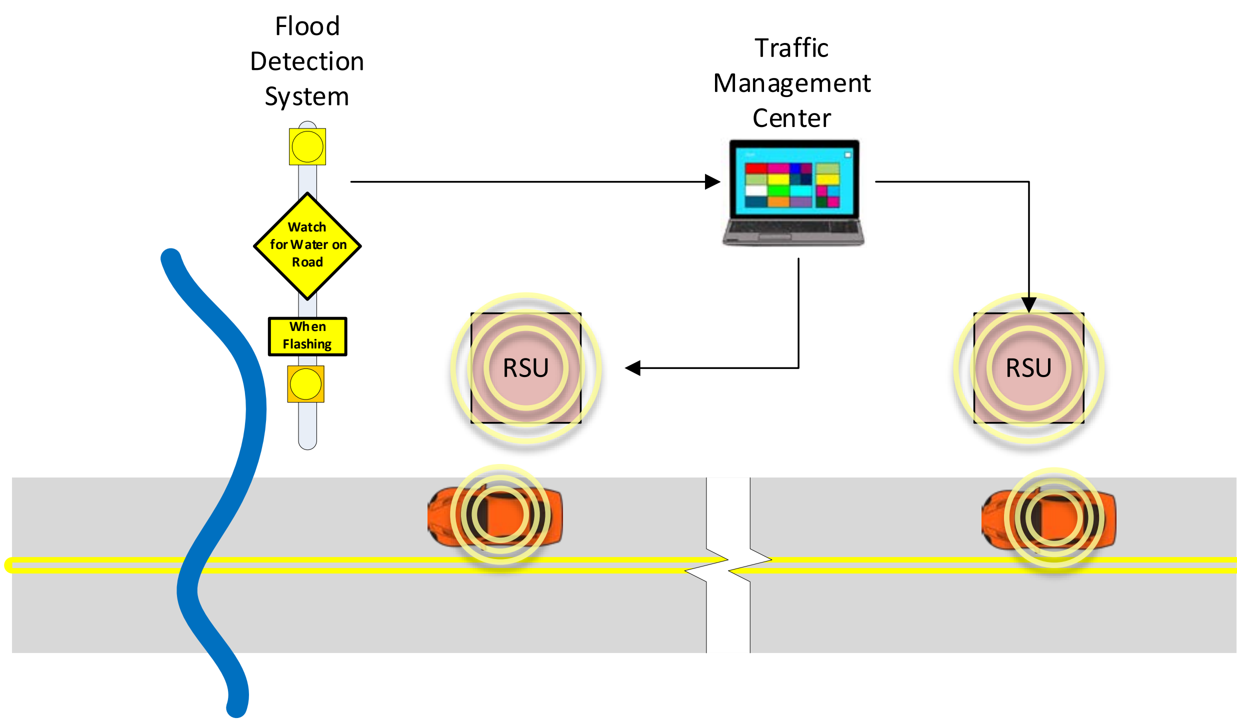
8.2 CONCEPT OF OPERATIONS

The CV FWS provides warning messages and alerts to travelers in CVs about a roadway's status in flood-prone areas, such as LWCs. The system integrates with existing traffic control systems (signs, markings, sensors, etc.) deployed at these crossings. The concept of operations from this system is as follows:

- The system is continuously receiving water depth readings from the flood gauge sensors located at the crossing. The flood gauge sensors continuously monitor water depth above the pavement at the lowest point in the crossing.
- When the system detects that the water level is rising in the crossing, it begins to broadcast an alert message that the crossing can become impassable in the immediate future due to rising water levels. The purpose of the message is to encourage drivers to use alternate routes and not enter the crossing.

- Once water levels reach a point where vehicles cannot traverse the crossing safely, the system automatically changes the roadside safety message's content to indicate that the crossing is closed and that drivers should seek alternate routes. Examples of the types of messages the system could broadcast include "Flooding. Road Closed. Do Not Enter" or "Road Closed Due to Flooding. Seek Alternate Routes."
- Under both conditions, the system notifies CVs upstream of the crossing, recommending that drivers use an alternate route. This notification provides vehicles with a location where diversion is still possible. Diversion opportunities could be several miles away from the crossing.

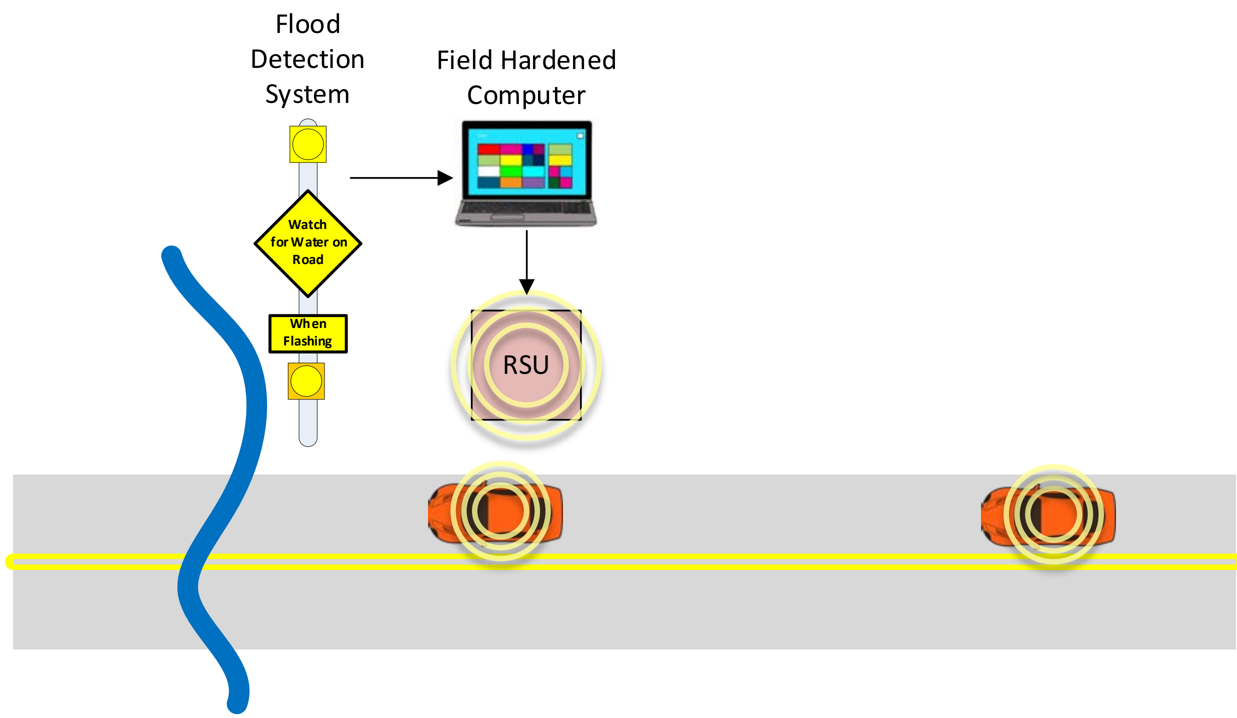
The researchers identified two different methods for implementing the concept. Figure 8-1 shows the first implementation method. With this implementation approach, the flood sensors at the crossing are tied directly to TxDOT's LoneStar Traffic Management Center Software System. Under this implementation, the TMC would connect directly to flood sensors at the crossing. The system would send water depth levels back to the TMC, and the LoneStar software would generate messages. The TMC would then be responsible for activating and managing the messages broadcast to the CVs. Additionally, alerts are provided to the TMC operators, allowing them to coordinate any additional activities, such as deploying safety personnel.



Source: Texas A&M Transportation Institute

Figure 8-1. TMC-Based Implementation of CV Flood Warning System.

The other manner of implementation is a standalone system. Implementers would install a field-hardened computer at or near the crossing location. This field-hardened computer would be responsible for receiving water depth information, determining the types of messages to be communicated to the CVs, and activating the communication devices. Under this implementation, the system would also notify the TMC when it activates, allowing the TMC operator to update or modify the message based on information available to the TMC. Figure 8-2 shows an example of this implementation.



Source: Texas A&M Transportation Institute

Figure 8-2. Standalone Implementation of CV Flood Warning System.

In addition to broadcasting alerts and warning messages to CVs, the system would also automatically activate a system of IIRPMs installed at the crossing. In Task 5, the researchers recommended that yellow IIRPMs be used to delineate the centerline of the roadway at locations where drivers regularly drive through high-water conditions and drive off the roadway. The researchers also recommended installing red IIRPMs across the lanes at the boundaries of the crossing. Automatically activating these systems during flooding events might reduce intrusion instances when the crossing is not traversable. The system would activate the yellow IIRPMs when water is present but the crossing is still traversable. The system would deactivate the yellow IIRPMs and activate the red transverse IIRPMs when water levels indicate the crossing is not traversable by vehicles. The red IIRPMs would stay illuminated until the water level recedes and the crossing becomes traversable again. Once the crossing is again traversable, the system would reactivate the yellow centerline IIRPMs. The system would deactivate all IIRPMs once the water levels recede below a user-defined threshold.

8.3 CV TECHNOLOGIES

The CV technology utilized in this project uses dedicated short-range communication (DSRC) equipment available as hardened commercial off-the-shelf (COTS) devices available from multiple vendors, such as Cohda and Savari. These devices undergo interoperability testing through OmniAir certification and leverage several standards, including SAE J2735, USDOT RSU 4.1 specification, IEEE 1609.3, IEEE 802.11, and SAE J2945. DSRC uses a portion of the dedicated 75 MHz of radio spectrum allocated for safety-critical vehicle applications in 1999. In December 2019, the Federal Communications Commission (FCC) under Ajit Pai initiated a Notice of Proposed Rulemaking to remove the dedicated 75 MHz from DSRC and reallocate the spectrum. Cellular vehicle to everything (C-V2X) retains a portion of the 75 MHz, while DSRC is no longer allocated spectrum. Due to the nature of the wireless signals, DSRC and C-V2X communication are incompatible at the physical layer (DSRC uses orthogonal frequency-division multiplexing with carrier-sense multiple access, while C-V2X uses single carrier frequency-division multiple access scheme). Fortunately, most of the COTS equipment operates dual-radio solutions and can support operating in the C-V2X spectrum. As the FCC rulemaking comes into effect, agencies can reconfigure or replace existing equipment to comply with these adjustments, and the capabilities of alerting drivers through V2X broadcast messaging will be retained.

CV communication is not limited strictly to V2X communication, and some companies offer applications that provide alerts to drivers through smartphone applications and other add-on capabilities. While DOTs do not connect directly to the vehicles operating these third-party applications, an application programming interface (API) has been created that provides this information to third-party companies and applications. These applications rely on DOT data and leverage communication channels such as long-term evolution to communicate with vehicles. The data fields available to third-party companies are prioritized under the Connected Vehicle Pooled Fund Study. A third-party company can gather information from DOTs by accessing an information feed that can include closed roads and provide these alerts to drivers. The Institute of Transportation Engineers, with the engagement of other standards bodies and organizations (*80*) is pursuing the standardization. Additionally, these third-party companies integrate with other navigation solutions such as Waze, allowing travelers to avoid taking routes that are impacted by LWC areas. By integrating with the TMC, additional information can be provided to travelers through DMS or website alerts. Center-to-center (C2C) communication mechanisms can allow TMCs to provide awareness of roads that are closed due to flooding to other TMCs or third-party companies directly.

8.4 USE CASES/OPERATIONAL SCENARIOS

The following subsections describe the use cases/operational scenarios that the researchers used to develop the system requirements and system architecture.

8.4.1 Local CV Flood Warning System Installation

This use case represents a situation in which the detection of flooding conditions and the issuing of traditional and CV alerts occur at the LWC location. In this use case, TxDOT would install flood-monitoring equipment at or near the flood-prone area. This equipment would consist of typical equipment that TxDOT installs at its flood-prone crossing areas. This equipment might include the following:

- Water-level sensors for monitoring the depth of water in the crossing.
- A base station for collecting and processing water depth information from multiple flood sensors.

- A flasher assembly with static flood warning signs for providing alerts to non-CV-equipped vehicles at the crossing.

A local control unit would be responsible for monitoring the output of the flood sensor equipment. Once the water levels reached predefined thresholds, the local control unit would activate the flashing beacon assemblies typically used by TxDOT at the LWC. The local control unit would also be responsible for activating any dynamic message display at the crossing, including IIRPMs or blank-out signs installed upstream of the crossing. The local control unit would also be responsible for activating the radio at the crossing to broadcast alert messages to CVs.

As part of the notification process, the local control unit would notify a TMC operator when it issued flood warning alerts. This notification could occur using simple text messaging or other protocols via a cellular connection to the TMC. The operator would then be responsible for verifying the alert conditions and adjusting the automated responses as appropriate.

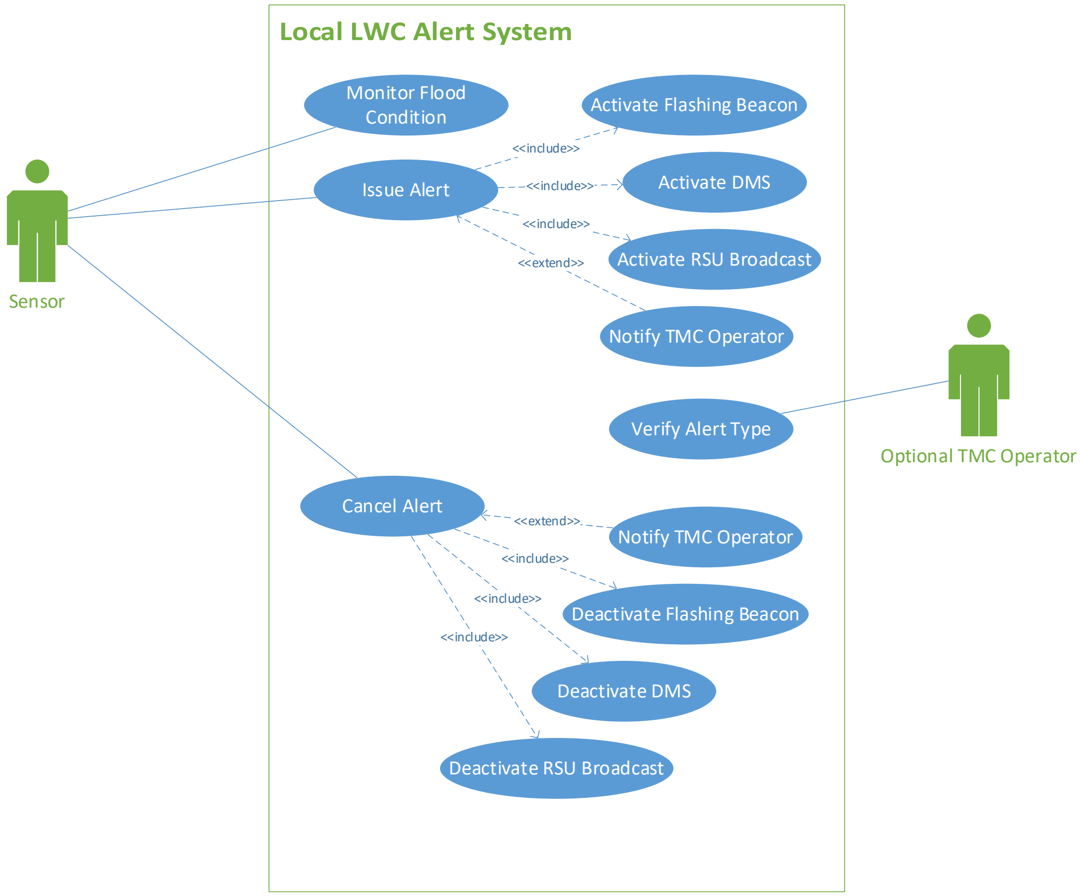
The local control unit would continue to monitor flood conditions at the crossing and update the alert messages as appropriate as needs changed. The system would continue to produce alerts if the water level remained above a specific threshold.

Once the water level in the crossing dropped below a set of thresholds defined by TxDOT, the local control unit would deactivate the system's alert message components. Deactivating the system would include deactivating the flasher assemblies, deactivating the IIRPM system, and canceling the broadcast of alert messages to CVs. Once the system deactivated the alert messaging component, the system would return to monitoring the water levels at the crossing for further changes.

Figure 8-3 depicts the functions performed by the various system components in this use case.

8.4.2 Centralized CV Flood Warning System Installation

Under this use case, some of the system's functional components would reside at a TMC instead of locally at the crossing. Sensor technology would still be required at the crossing to receive water depth information. The sensors would transmit the water depth information to the TMC. Software at the TMC would then monitor the crossing status and determine whether to activate the CV alert systems. The CV FWS component would notify the operator if water levels in the crossing exceeded a preset threshold. The operator would then verify that the information about the crossing was accurate. The operator would then select and implement the appropriate alert messages based on the verified conditions. The alert messaging might include activating one or more components of the alert system (the flasher assembly at the crossing, the IIRPM system, and the CV alert messaging component).

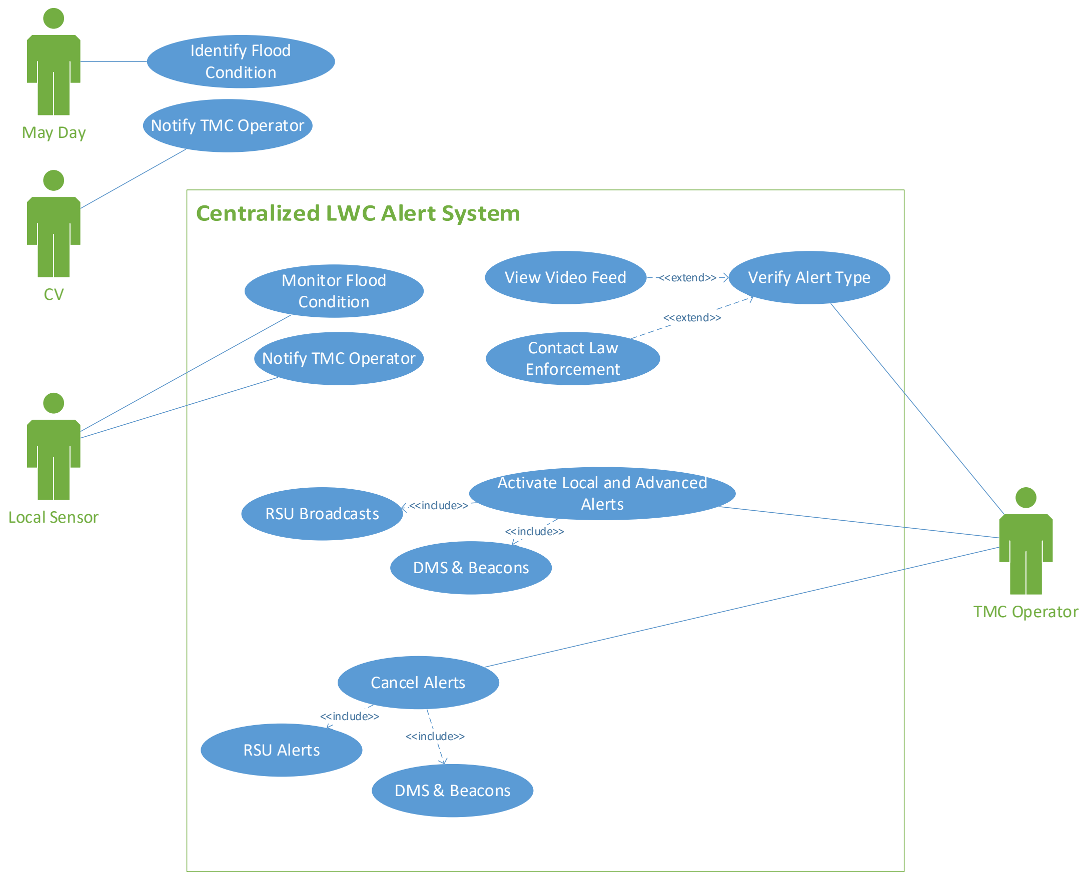


Source: Texas A&M Transportation Institute

Figure 8-3. Use Case Diagram of Standalone CV Flood Warning System.

The operator would be responsible for verifying the conditions at the crossing. Once the crossing conditions were verified, the operator would then be responsible for activating the alert messages. The operator would select an appropriate message from a library of preformatted and encoded messages for the crossing. Once the operator selected the appropriate message, the system would then send the encoded roadside safety message (RSM) to the DSRC radio at the crossing, where the radio would broadcast the message in a "Store and Repeat" mode. The message would continue to broadcast until (a) the operator either revised the message or cleared (deactivated) the message, or (b) the time-to-live value on the message expired. Once the system deactivated the messages, it would return to its normal standby state. The system would continuously monitor the crossing's status and notify the operator when the crossing's conditions required an update to the system. Updating might include altering the content of the CV messages and deactivating the system as conditions warranted.

Figure 8-4 depicts the functions performed by the various system components in this use case.



Source: Texas A&M Transportation Institute

Figure 8-4. Use Case Diagram of Centralized CV Flood Warning System.

8.5 SYSTEM REQUIREMENTS

Based on these use cases, the researchers identified the high-level requirements for the system. Table 8-1 lists these high-level system requirements.

Table 8-1. High-Level System Requirements of Proposed CV Flood Warning System.

System Requirement Number	Description	Rationale
1. DETECTION		
1.1	The CV FWS shall be capable of producing alerts based on water flow conditions.	The system needs to produce alerts that provide advanced warning to travelers that an LWC or flood-prone area is not traversable due to high water in the area.
1.1.1	The CV FWS shall be capable of determining when water is present in the crossing but the crossing is still traversable.	This level will allow the operator to set a threshold for allowing alerts when water is present but the crossing is still traversable by vehicles.
1.1.2	The CV FWS shall be capable of determining when a crossing is not traversable by vehicle due to flooding.	This level will allow the operator to set a threshold for allowing alerts when water is present and the crossing is not traversable by vehicles.
1.2	The CV FWS shall be capable of receiving information from the infrastructure-based flood sensor technologies.	This requirement allows the integration of existing TxDOT flood warning sensors into the system.
1.2.1	The CV FWS shall be capable of receiving information about the status of an LWC (flooded/not flooded).	This requirement allows the integration of existing TxDOT flood warning sensors into the system.
1.2.2	The CV FWS shall be capable of receiving information about the current depth of water at the LWC.	This requirement allows the integration of existing TxDOT flood warning sensors into the system.
1.2.3	The CV FWS shall be capable of receiving information about the current flow rate of water through the LWC.	This requirement allows the integration of existing TxDOT flood warning sensors into the system.
1.3	The CV FWS shall be capable of receiving information from CVs traveling near the crossing.	This requirement allows the integration of information from CV vehicles into the system.
1.3.1	The CV FWS shall be capable of receiving BSMs from equipped vehicles.	This requirement allows the integration of information from CV vehicles into the system.
1.3.2	The CV FWS shall be capable of receiving Mayday alerts from equipped vehicles.	This requirement allows the integration of information from CV vehicles into the system.

System Requirement Number	Description	Rationale
1.4	The CV FWS shall be capable of accepting input from a traffic management entity.	This requirement allows TxDOT TMC operators to activate/manage the system.
1.4.1	The CV FWS shall be capable of accepting configuration inputs from a TMC.	This requirement allows TxDOT TMC operators to activate/manage the system.
1.4.2	The CV FWS shall be capable of sending inputs about the status of the LWC to the TMC.	This requirement allows TxDOT TMC operators to activate/manage the system.
2. Verification		
2.1	The CV FWS shall have the capability to allow operators to verify the detection of flooding conditions in an LWC.	This requirement allows TxDOT TMC operators to activate/manage/override the system.
2.1.1	The CV FWS shall allow the operator to change the crossing status information.	This requirement allows TxDOT TMC operators to activate/modify the system based on other knowledge from the crossing.
2.1.2	The CV FWS shall allow the operator to control the activation of the warning beacons.	This requirement allows the TxDOT TMC operator to activate/ deactivate the flasher assemblies remotely.
2.1.3	The CV FWS shall allow the operator to control the activation of the LED pavement marker system.	This requirement allows the TxDOT TMC operator to activate/ deactivate the LED pavement marking system remotely.
2.1.4	The CV FWS shall allow the operator to control the activation of the DSRC radio to broadcast alert messages.	This requirement allows the TxDOT TMC operator to activate/ deactivate the DSRC radios remotely.
2.1.5	The CV FWS shall allow the operator to modify the content of the roadside message broadcast over the RSU.	This requirement allows the TxDOT TMC operator to modify the RSM based on other information.
2.2	The CV FWS shall maintain a log of all changes made to the alert messages.	This requirement allows the system to log all actions/changes/modifications to post-event review system parameters.
3. Notification		
3.1	The CV FWS shall notify the TMC when it detects flooding conditions.	This requirement allows for the activation of the system.

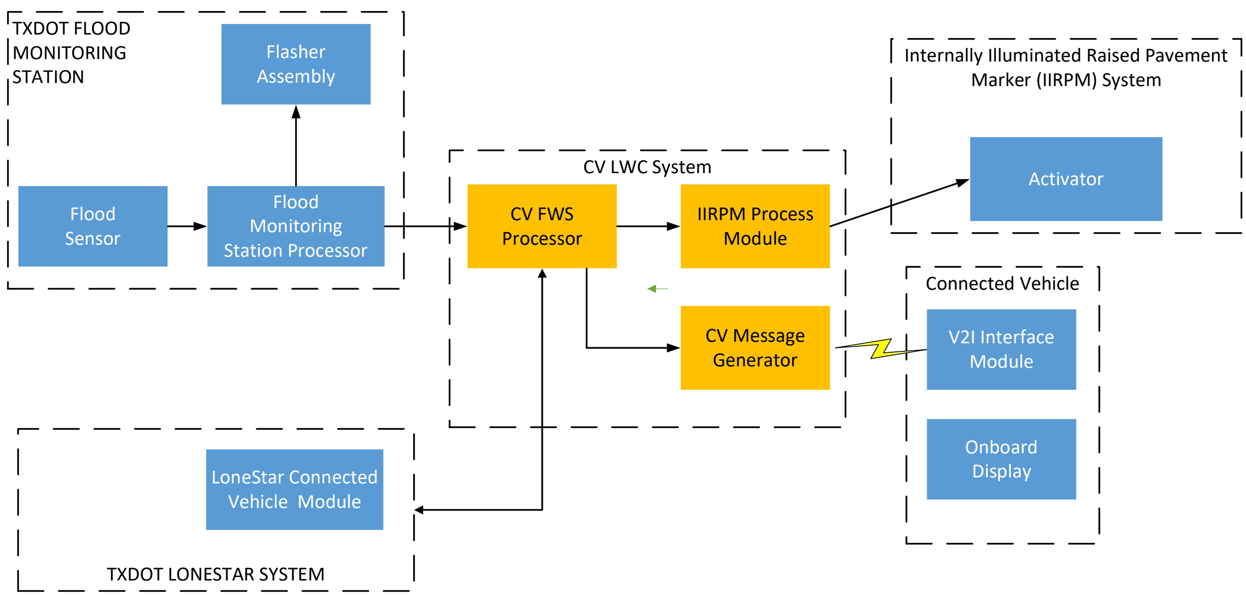
System Requirement Number	Description	Rationale
3.1.1	The CV FWS shall notify the TMC when water depth levels exceed a threshold for producing alerts related to rising water levels.	This requirement allows for the activation of WATCH alerts as the water levels are rising/receding and the crossing is traversable by motorists.
3.1.2	The CV FWS shall notify the TMC when water depth levels exceed a threshold for producing warning alerts related to rising water levels.	This requirement allows for the activation of WARNING alerts as the water levels are rising/receding and the crossing is traversable by motorists.
3.1.3	The CV FWS shall notify the TMC operator when water depth levels have returned to normal through the crossing.	This requirement allows for the clearing of all alerts (WATCHES and WARNINGS) from the system.
3.1.4	The CV FWS shall notify the TMC operator when there is a disruption in communication to the flood sensors.	This requirement allows the TMC to detect when the system is not receiving inputs from the flood sensors.
3.2	The CV FWS shall communicate the operational status of the flood warning flasher assembly to the TMC operator.	This requirement allows the TMC to detect if a disruption exists in the communications to the flasher assembly.
3.3	The CV FWS shall communicate the operational status of the LED pavement marking system to the TMC operator.	This requirement allows the TMC to detect if a disruption exists in the communications to the internally illuminated pavement marking system.
3.4	The CV FWS shall have the ability to communicate the operational status of the DSRC radio to the TMC operator.	This requirement allows the TMC to detect if a disruption exists in the communications to the DSRC radio.
4. ISSUING ALERTS		
4.1	The CV FWS shall have the capability to produce two levels of alerts (WATCHES and WARNINGS) based on water levels at the crossing.	This requirement allows for the TMC to issue two levels of alerts: WATCHES and WARNINGS.
4.1.1	The CV FWS shall have the capability to generate a J2735 RSM when the system detects water levels at or above the WATCH threshold.	This requirement allows the system to generate messages specific to the WATCH condition automatically.

System Requirement Number	Description	Rationale
4.1.2	The CV FWS shall have the capability to generate a J2735 RSM when the system detects water levels at or above the WARNING threshold.	This requirement allows the system to generate messages specific to the WARNING condition automatically.
4.2	The CV FWS shall have the capability of activating/deactivating the flood warning flasher assembly at the crossing.	This requirement allows the system to activate/deactivate the flasher assembly at the crossing automatically.
4.3	The CV FWS shall have the capability of activating/deactivating the LED pavement marker system at the crossing.	This requirement allows the system to automatically activate/ deactivate the LED pavement marking system at the crossing.
4.4	The CV FWS shall maintain a log of all activations/deactivations of the system components.	This requirement allows the TMC operator to conduct a post-event review of the performance of the system.

8.6 LOGICAL ARCHITECTURE

Figure 8-5 shows the logical architecture of the proposed CV FWS. The primary functions of the components of the CV FWS are as follows:

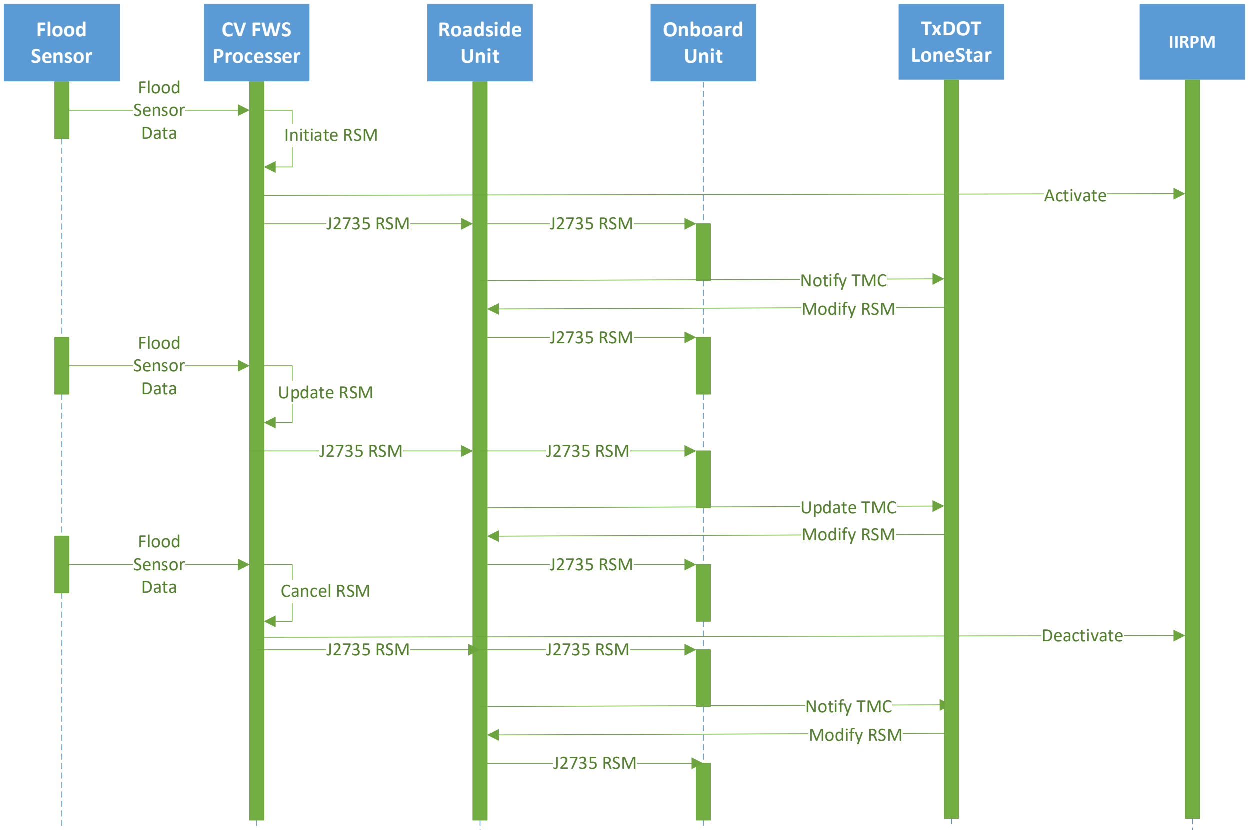
- *CV FWS Processor*—This processor is responsible for gathering the information about the status of the crossing from the flood-monitoring station. The processor then determines the state of the crossing (open, open with water, closed).
- *IIRPM Process Module*—The IIRPM is responsible for activating the IIRPMs at the crossing. The processor receives a request to activate the system from the CV FWS and then energizes the system. The same processor is responsible for deenergizing the IIRPM system when not needed at the crossing.
- *CV Message Generator*—This component is responsible for formulating and properly encoding the status message about the crossing in a proper J2735 RSM format. The component is also responsible for sending the message to the V2X interface devices.



Source: Texas A&M Transportation Institute

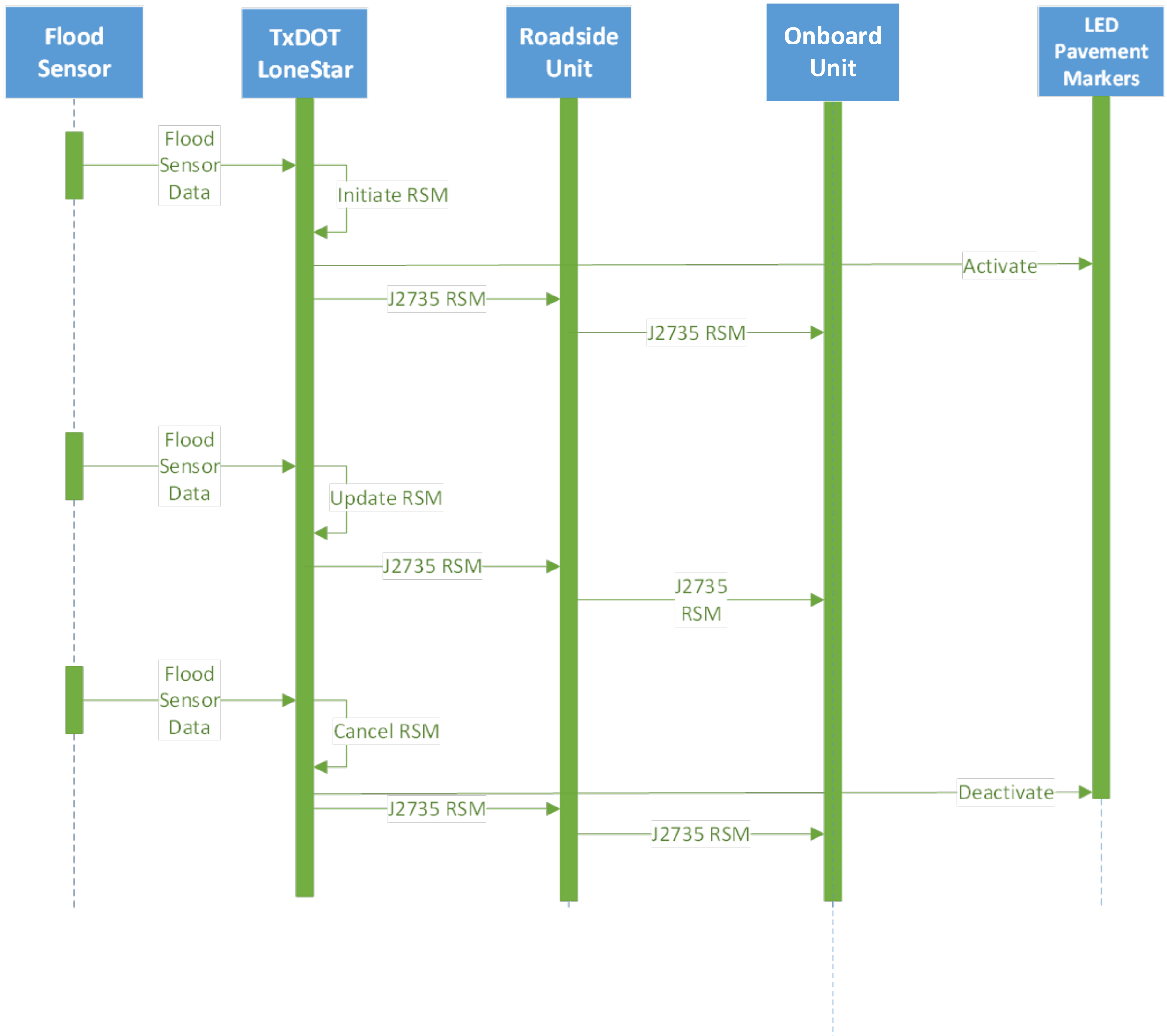
Figure 8-5. Proposed Logical Architecture for CV Flood Warning System.

Figure 8-6 and Figure 8-7 show the information exchange between the system components. Figure 8-6 shows the information exchange for the local CV FWS installation, while Figure 8-7 shows the information exchange for the centralized CV FWS installation.



Source: Texas A&M Transportation Institute

Figure 8-6. Information Exchange between System Components—Local CV Flood Warning System Installation.



Source: Texas A&M Transportation Institute

Figure 8-7. Information Exchange between System Components—Centralized CV Flood Warning System Installation.

In the local CV FWS implementation, the researchers distributed the data processing, message generation, and decision-making between the RSU and the CV FWS processor. In the centralized CV FWS installation, most data processing, message generation, and decision-making occur within the TxDOT LoneStar environment. The advantage of integrating the CV FWS into the TxDOT LoneStar system is that the CV FWS would be one of many applications that take advantage of CV data. Integrating this application with others into LoneStar would allow TxDOT to build a suite of applications that capitalize on the CV technologies' data, not just a flood warning system.

8.7 GENERATION OF CV ALERT MESSAGES

The system would utilize the SAE J2735 RSM for broadcasting alert messages to CVs. Each crossing would have an RSU located near the flood-monitoring equipment. As shown in Figure 8-8, the researchers would establish geofenced activation zones around each crossing. As CVs entered the activation zone around the crossing (i.e., the shaded area in the figure), they would receive the RSM alert message. Vehicles outside the geofenced area might receive the RSM but would essentially ignore the message since it would not pertain to them. Figure 8-9 shows an example of vehicles located in the activation zone that would receive RSM alerts.

Source: Southwest Research Institute

Figure 8-8. Geofenced Message Activation Zone.

Source: Southwest Research Institute

Figure 8-9. Illustration of Vehicles inside CV Flood Warning System Message Activation Zone.

Each RSM would contain the following information related to the status of the LWC:

- Start and end time of the message—this information would define the period for which the alert was applicable.
- “Cause” codes—this information would define the type of status of the roadway at the crossing (e.g., road closed) and the cause of the closure (e.g., flooding).
- Reference point information—this information would define the crossing location and include the latitude and longitude of the LWC and heading and tolerance information to target messages to vehicles heading toward the crossing.
- Descriptive name—this would be the common name of the LWC warning information.
- Geometric coordinates—this information would define the geofence of the approach region to the crossing.
- Alert message—this alert message would be a similarly worded message to what an agency would display on a DMS.

Using the RSM format would allow TxDOT to provide a simple alert message to CVs. As noted previously, the content of the alert message would be similar to what TxDOT provides on its DMSs.

The researchers envision the system producing two types of messages: WATCH messages and WARNING messages. The system would use WATCH messages to provide information when the crossing is still traversable by vehicles. Examples of WATCH messages include the following:

- Watch for Water on Roadway. Turn Around. Don’t Drown.
- Water Ahead. Use Alternate Routes.
- Flooding Likely. Expect Road Closures.

The system would issue a WARNING message when the crossing is no longer traversable by vehicles. Examples of WARNING messages are the following:

- Flooding Ahead. Road Closed. Do Not Enter.
- Gibson Creek Flooded. Road Closed. Use Alternate Routes.
- SH 6 Closed Due to Flooding. Use Alternate Routes.
- High Water Ahead. Turn Around. Don’t Drown.

The researchers designed the system to convey alerts and warnings using DSRC technology. DSRC is an open-source, wireless communications technology that enables vehicles to communicate with each other and other road users directly using the 5.9-GHz band. This technology allows vehicles to communicate with each other and with the infrastructure 10 times per second. Most current CV deployments use DSRC; however, agencies can adapt the CV FWS to operate using any C-V2X technology (e.g., radio frequency identification, Worldwide Interoperability for Microwave Access [WiMAX], Wi-Fi, Bluetooth, and cellular communication). The researchers are currently exploring the potential of using cellular technologies as an alternative to DSRC.

Chapter 9. CONTROLLED ENVIRONMENT TESTING DEMONSTRATION

9.1 INTRODUCTION

The researchers developed a proof-of-concept prototype for demonstrating the functionality and values of a CV application for disseminating information about flooded LWCs. The researchers designed the applications to operate with a typical flood sensing system used in the field by TxDOT. These systems generally consist of sensors for detecting water depth levels and activating the flasher assembly. The system then would generate flood warning alerts and broadcast this information to CVs through an RSU using DSRC. The researchers equipped a test vehicle with an onboard unit (OBU) for receiving messages from the infrastructure. The researchers also equipped the vehicles with a portable tablet for displaying the alerts and warning information to the test vehicle operator.

9.2 TESTING CONFIGURATION

The researchers tested the prototype by simulating a flooding event at a designated location at the Texas A&M University System RELLIS Campus. The researchers simulated flood conditions by placing the flood sensors in buckets of water to activate the flood detection system. The researchers designed and tested messages for vehicles approaching and departing the crossing area under different flood conditions. The researchers also defined an area parallel to the flood area where the test vehicle would receive a diversion message associated with the flood area. Figure 9-1 shows how the researchers configured the test area for proof-of-concept testing.

9.2.1 Flood Detection

The researchers installed a flood detection system adjacent to the designated area. The system uses the same technology as the standard TxDOT flood detection and warning system. Figure 9-2 shows the equipment, which consists of a detection station installed on a pole and a flasher assembly that activates when the roadway floods.

The researchers located the flasher assembly approximately 500 ft south of the test location. Figure 9-3 shows the flasher assembly, which faces back toward the sensor station so that the test administrator can see when the flasher assembly is activated.

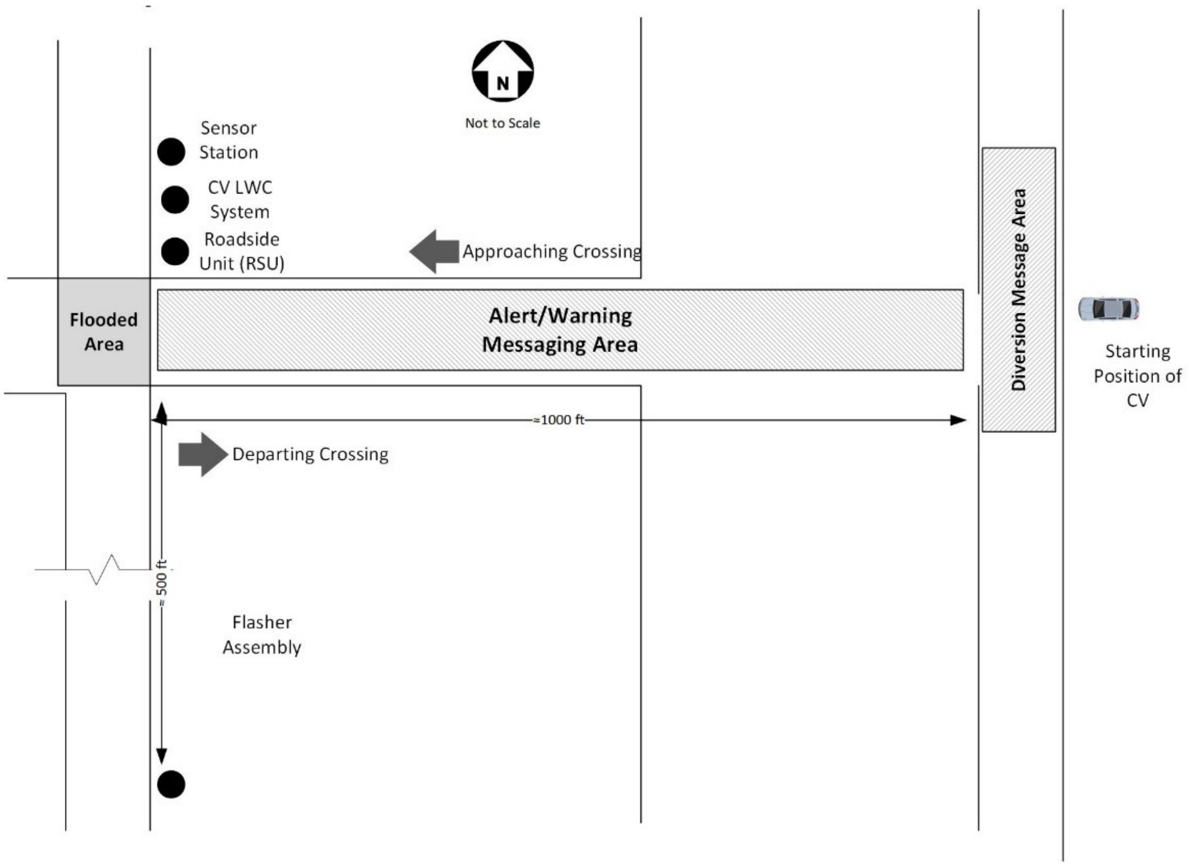


Figure 9-1. Configuration of Test Area for Proof-of-Concept Testing.

Figure 9-2. Flood Detection System.

Figure 9-3. Flood Warning Flasher Assembly.

Figure 9-4 shows how the researchers simulated flooded conditions at the crossings. The flood detection system used two water depth sensors to detect different stages of a flood event. Agencies use the first detector to activate the flasher assembly when water levels rise but the crossing is still passable. Agencies will often use the second sensor to lower gate arms (similar to railroad crossing gates) when the water level is impassable, closing the crossing and prohibiting motorists from entering the flooded area.

The researchers used two buckets of water to simulate different water depths to activate each flood detection system stage. Each bucket of water represented a particular level of water over the roadway. The initial starting position of each sensor was next to its designated bucket. The researchers used two buckets of water to simulate the rising and dissipating water levels. The first sensor emulated water being detected on the roadway and activated the crossing's flashing assembly (a Level 1 alert). The researchers used the second sensor to simulate water depths when the LWC was closed due to high water (a Level 2 alert). The researchers then generated different CV messages to represent different stages of the flood event. The message associated with a Level 1 alert was "Watch for Water on Roadway. Turn Around. Don't Drown." The message associated with a Level 2 alert was "Road Closed Due to Flooding. Turn Around. Don't Drown." The flood detection systems also produced a contact closure when each sensor was activated.

Figure 9-4. Bucket Representing Water over Roadway for Case 1.

9.2.2 LWC CV Application

The LWC CV application was installed on a laptop computer and connected directly to the sensor station. The researchers prepared an application that monitored the output of the flood detection sensors to trigger different preprogrammed alert messages based on each sensor's status. The LWC application caused the RSU to broadcast the appropriate messages depending upon which sensor was active. The test deployment used an RSU on a pole adjacent to the test area. Figure 9-5 shows how the researchers deployed the application in this prototype testing.

Figure 9-5. Test Configuration of LWC CV Application.

Figure 9-6 shows the portable CV unit the researchers equipped in the test vehicle. The test unit contained an OBU to receive and decode RSMs broadcast from an RSU. Figure 9-7 shows the portable handheld unit located in the front seat with the driver that displayed the warning messages.

9.2.3 Display Messages

The researchers designed the application to use RSMs to alert motorists of the crossing conditions. The system generated three levels of messages:

- Level 1: Alert Message—The application produced this message when the system first detected water over the roadway but the crossing was still passable.
- Level 2: Warning Message—The application produced this message to warn drivers that the crossing was closed because water levels made it not passible.
- Diversion Message—The application produced this message on routes leading up to the crossing. The purpose of this message was to warn drivers not to go down the roadway because the crossing was closed due to flood conditions.

Figure 9-8 through Figure 9-10 contain the message alerts used in the testing.

Figure 9-6. Portable OBU Test Unit.

Figure 9-7. Portable Tablet for Displaying CV Alert Messages.

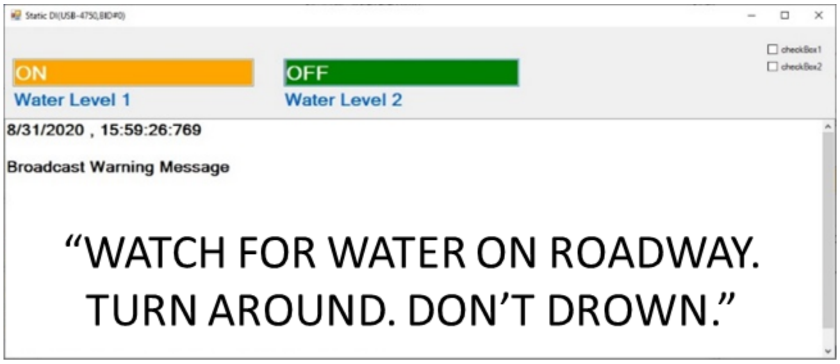


Figure 9-8. Content of a Level 1 LWC Alert.

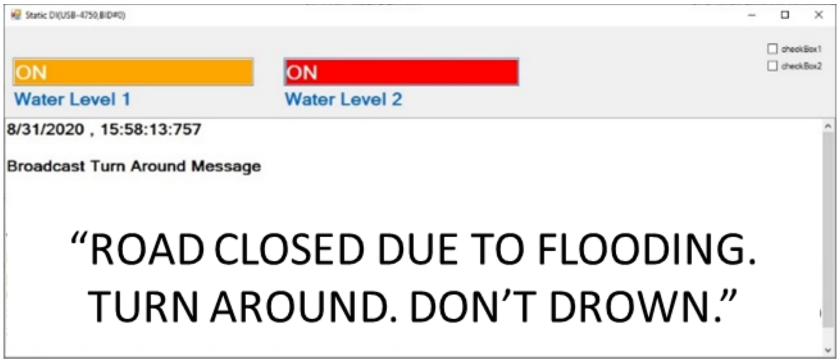


Figure 9-9. Content of a Level 2 LWC Alert.

Figure 9-10. Content of an LWC Diversion Alert.

9.3 TEST SCENARIOS

The researchers identified three test deployment scenarios for conducting verification testing. This section describes each of the test scenarios that the researchers used in the demonstration testing.

9.3.1 Scenario 1: Alerts and Warning Issued through a Standalone Deployment

The primary purpose of this test was to demonstrate the use of CV technologies directly integrated with a flood detection system to broadcast alerts and warning messages associated with an LWC or flood-prone section of a roadway. In this scenario, the CV system activated two CV messages based on the flood sensors' status—a Level 1 alert that notified drivers to watch for water on the roadway and a Level 2 warning that told drivers that the crossing was closed due to flooding. Figure 9-11 shows the configuration of the test area at the testbed.

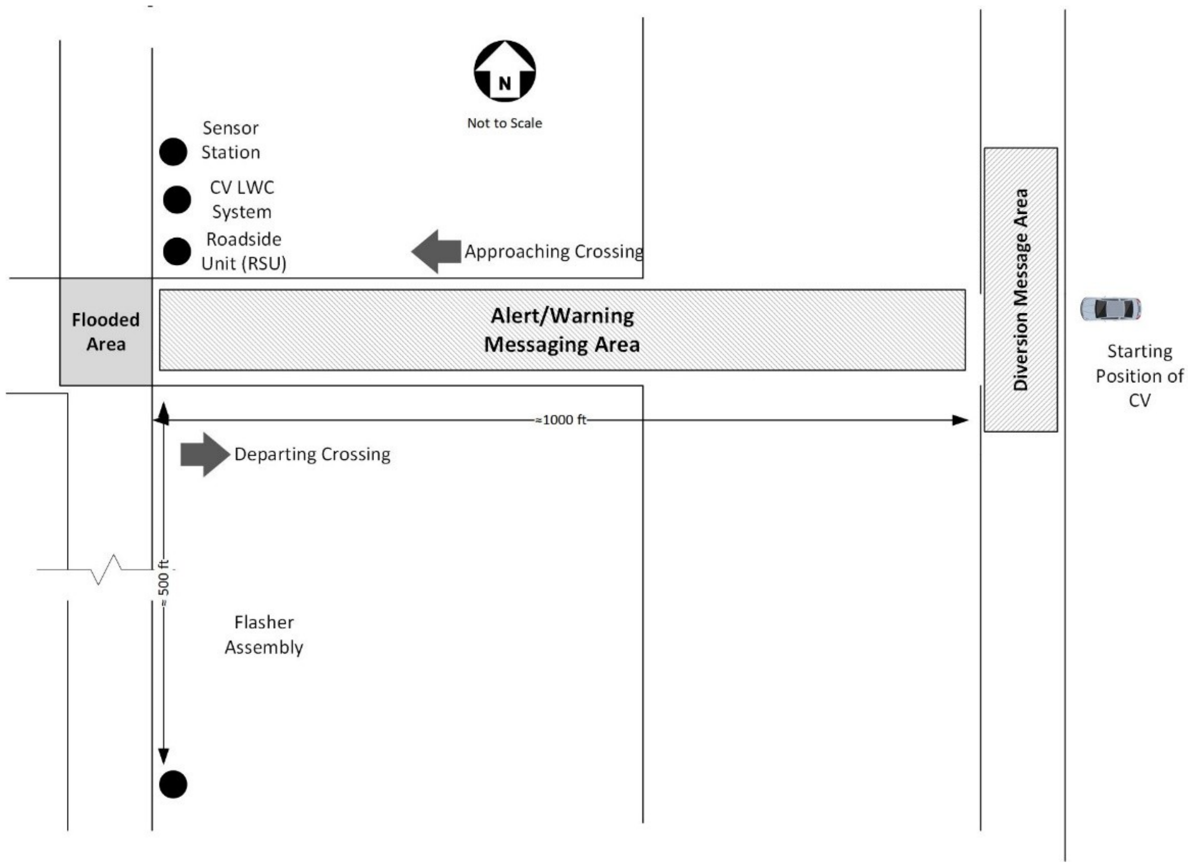


Figure 9-11. Configuration of Test Area for Case 1.

9.3.2 Scenario 2: TxDOT's LoneStar Traffic Management Software

For this test, the researchers integrated the flood detection system with TxDOT's LoneStar Traffic Management System. The LoneStar system monitored the status of the flood sensors and activated the broadcast of the CV messages (Level 1 and Level 2 alerts) to the RSU via a cellular modem. The content of the message depended on the water levels measured by the sensors. Figure 9-12 shows the configuration of the test area at the testbed.

The equipment configuration was the same as Scenario 1 except that the TxDOT LoneStar Traffic Management System monitored the status of the flood sensors. LoneStar connected to the flood detection system via a cellular modem. For this test, the researchers used a virtual test version of the LoneStar system running in the Southwest Research Institute's offices in San Antonio. The virtual LoneStar system determined which message was appropriate to broadcast to the CVs based on the flood detection sensors' status. The LoneStar CV module broadcasted the same alerts as in Scenario 1.

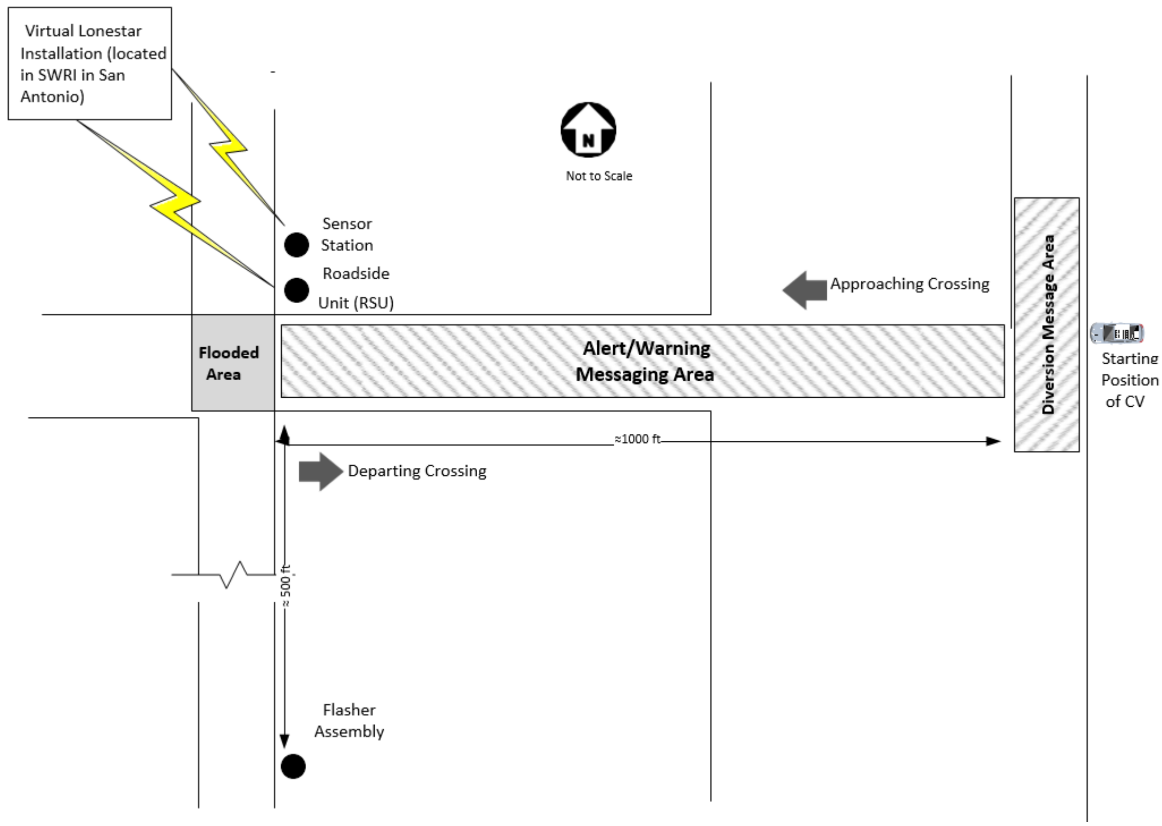


Figure 9-12. Configuration of Test Area for Case 2.

9.3.3 Scenario 3: Diversion Messages

This test's primary purpose was to demonstrate that the LoneStar Traffic Management System can broadcast diversion messages to motorists upstream of LWCs or flood-prone sections of roadways via an RSU. This test used the same configuration as Test Case 2. For this test, the researchers established a diversion message zone on a roadway facility that paralleled the crossing area. When the system detected flooding in the crossing, the system generated a diversion message indicating that the crossing was closed due to flooding and that the vehicle should continue straight on its current path. This test used the TxDOT LoneStar version of the application to monitor the flood sensors' status and generate the CV diversion message. Figure 9-13 shows the configuration of the test area at the testbed.

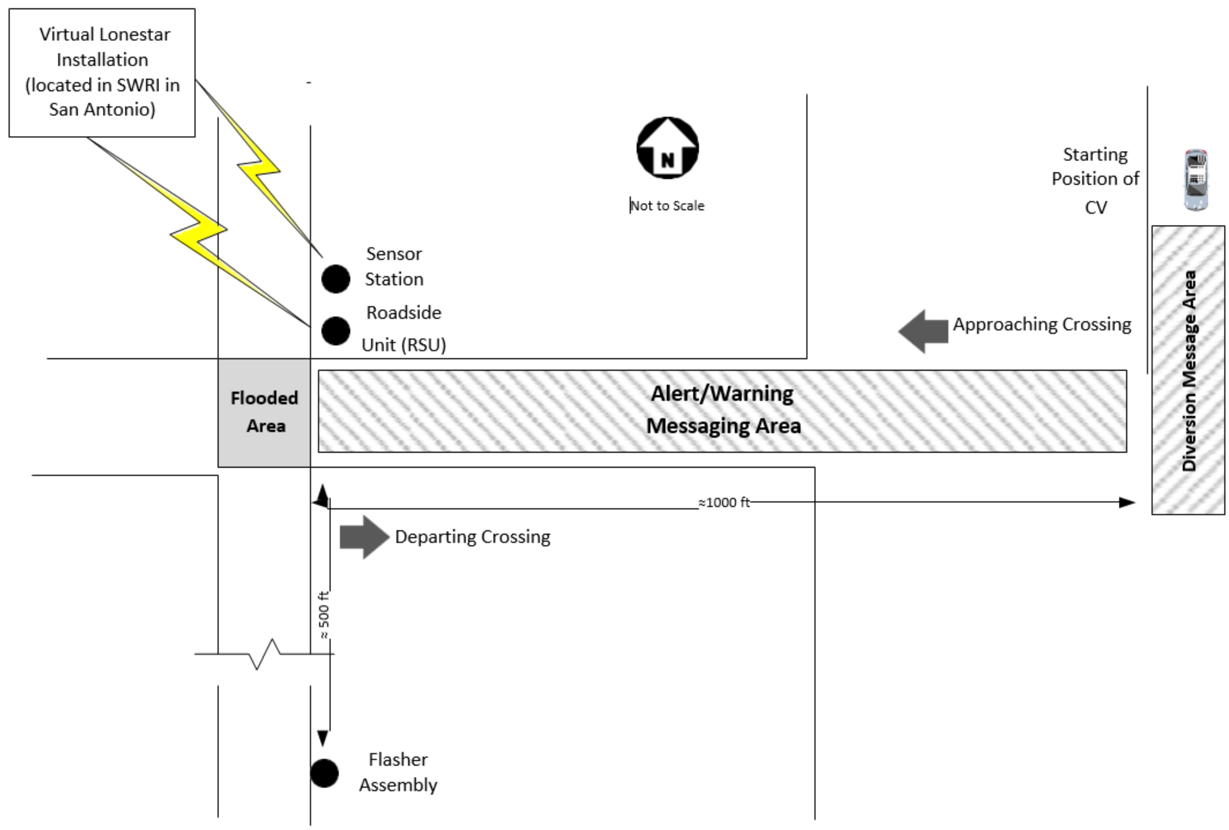


Figure 9-13. Configuration of Test Area for Case 3.

9.4 TEST PROCEDURE/SCRIPTS

The researchers developed test procedures/scripts to verify the operation of the prototype system. The researchers used the same general test procedures for each of the test scenarios. This section provides an overview of the test procedures.

9.4.1 No Flood Sensors Active

The purpose of this initial test was to verify that the CV did not receive any alerts or warnings if none of the flood sensors were activated. For this test, the researchers positioned the CV outside the area where a driver would receive an alert/warning message area. The test administrator verified that none of the flood sensors were active. When ready, the test administrator instructed the driver of the CV to drive through the designated flood area. The driver reported any messages or alerts displayed on the in-vehicle display to the test administrator. The test administrator recorded messages received by the vehicle as it approached and left the simulated flood area. The driver should not receive any warning or alerts either approaching or departing the designated flood area with no flood sensors active.

9.4.2 Level 1 Flood Sensors Active

This test aimed to verify that the CV received only Level 1 warnings when the sensor was active. For this test, the CV was positioned upstream of the simulated flood area. When ready, the test administrator placed the first sensor in a bucket to simulate rising water in the flooded area. This action caused the flasher assembly to activate. After the flasher assembly was active, the test administrator directed the driver of the CV to drive toward and then through the designated flooded area. The driver indicated to the test administrator the content of any message received as the vehicle approached and departed the simulated flood area. The test administrator recorded the response of the message displayed to the driver. In this test, the drivers were expected to receive a Level 1 warning message as the vehicle was approaching the flooded area. Drivers traveling away from the simulated flood area were not expected to receive any messages.

9.4.3 Level 2 Flood Sensors Active

The purpose of this test was to determine whether a CV correctly received a Level 2 alert message that the crossing was closed. As in the previous test, the CV's initial starting position was approximately 250 ft upstream of the simulated flood area. The test administrator submerged the Level 1 and Level 2 sensors in buckets of water to simulate that the crossing was now closed due to flooding. After placing Sensor 2 in the test bucket, the test administrator directed the driver of the CV to drive through the simulated flood area and report the content of any message displayed to the driver as the vehicle approached and then departed the designated LWC. The test administrator then recorded the message content displayed to the driver. The researchers expected that drivers traveling toward the crossing would receive an alert message indicating that the crossing was closed due to high water, while drivers traveling away from the LWC would not receive any message.

9.5 DEMONSTRATION RESULTS

The researchers used formalized test plans to demonstrate the CV LWC system's functionality. The test plans provided formal procedures for each test scenario. The test plans documented the conditions simulated at the crossing, the procedures for conducting each test, and the expected results of a successful demonstration test. The researchers compared the system's observed performance to its expected performance to identify the demonstration's successful completion. Appendix C contains the formalized test plans used by the researchers to conduct the demonstration testing. Raw video footage of the demonstration test cases can be found at https://youtu.be/7uFXL_bgOP8.

The demonstration's findings showed that CV technologies could be successfully integrated with automated flood detection systems to produce alerts and warning messages to drivers in CVs. The demonstration proved that TxDOT could either deploy this technology through a standalone application where everything is located in the field or through a TMC using the LoneStar system.

Chapter 10. ENHANCED LOW-WATER SIGNING AND MARKING PLANS

10.1 INTRODUCTION

This chapter summarizes work performed in Task 9. This task's objective was to develop and implement innovative signing and marking plans to improve drivers' situational awareness of LWCs.

10.2 TEST DEPLOYMENTS

Members of the project team worked with TxDOT representatives from the Bryan and Beaumont Districts to identify potential LWCs. The researchers conducted both daytime and nighttime investigations of multiple LWCs—on TxDOT-operated facilities in both the Bryan and Beaumont Districts—that might serve as potential test sites for enhanced delineation through the LWCs. The researchers did not consider using IIRPMs or an active warning system for this task. The researchers focused on using passive technologies (signs, markings, and RRPMs) to improve driver situational awareness.

10.2.1 Bryan District

The Bryan District's director of transportation operations identified approximately 10 sites in the Bryan District subject to flooding during heavy or continuous rainfall events. After meeting with the director to review the sites, the researchers identified five sites close to Bryan–College Station for further field investigation. The researchers conducted site reviews of each of these locations during February and March 2020. After reviewing these sites, the researchers selected two potential deployment sites for improved delineation through the LWCs. Figure 10-1 is a site map showing the location of the two sites chosen in the Bryan District. The following subsections provide descriptions and proposed designs for each of these sites.

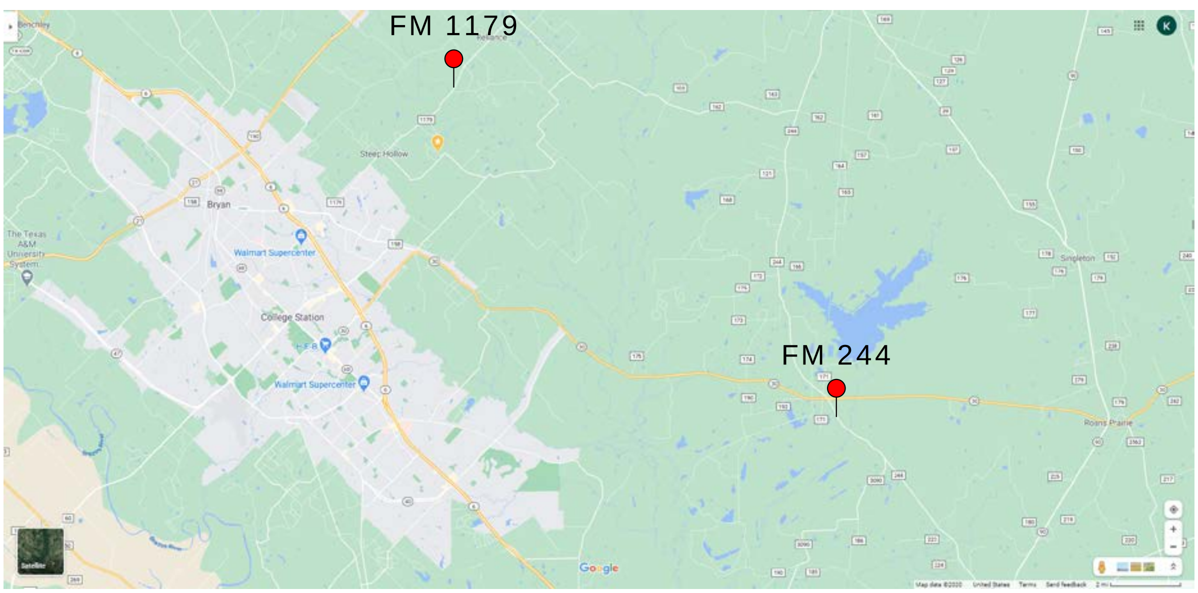


Figure 10-1. Location of Selected LWC Sites in the Bryan District.

10.2.1.1 FM 244

The first site selected as a candidate for improvement delineation was FM 244 near Gibbons Creek, south of Carlos, Texas. The site is located approximately 25 miles from Bryan–College Station. FM 244 is a two-lane state-maintained highway. The roadway section prone to flooding is in a low-lying area south of the actual creek crossing. Three bridge structures over portions of Gibbons Creek feed water into the low-lying area. Figure 10-2 is a photograph of the roadway approaching the flood-prone area from the north, heading southbound on FM 244. Figure 10-3 shows the same flood-prone area coming from the south, heading northbound on FM 244.

Figure 10-2. FM 244 (near Carlos, Texas) North of Gibbons Creek LWC, Heading Southbound.

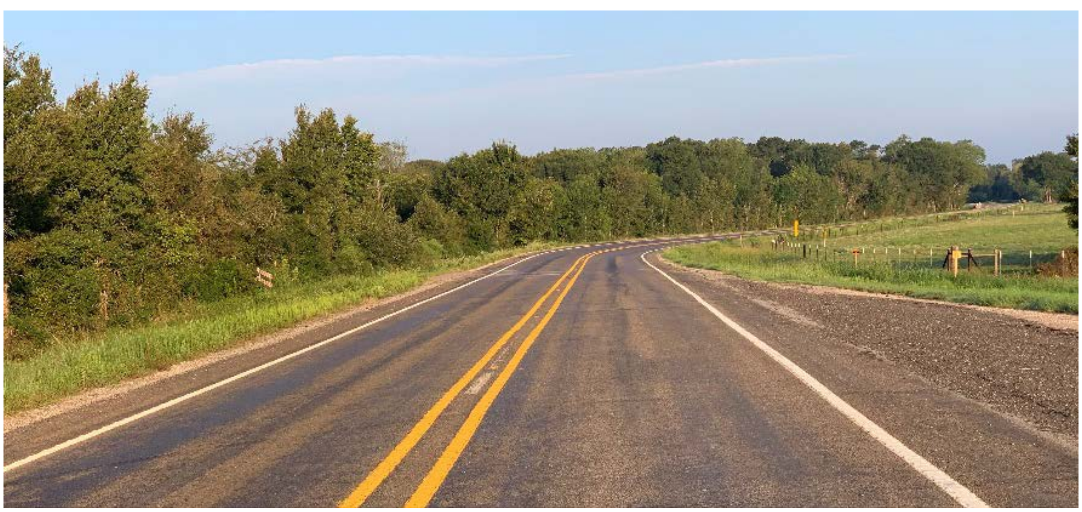


Figure 10-3. FM 244 (near Carlos, Texas) South of Gibbons Creek LWC, Heading Northbound.

TxDOT has installed W8-18 "ROAD MAY FLOOD" warning signs in both directions approaching the crossing and a W8-19 flood depth gauge in the approximate low point of the flood area. Figure 10-4 shows a map of the approximate location of the existing signs approaching the site. TxDOT has also installed raised profile markers on both edge lines and the centerline strips. These profile markers act as rumble strips for errant vehicles that might be departing the roadway. The site also has yellow RRPMs on approximately 40-ft centers throughout the pavement area. Both the signs and markings appear to be in a good state of repair.

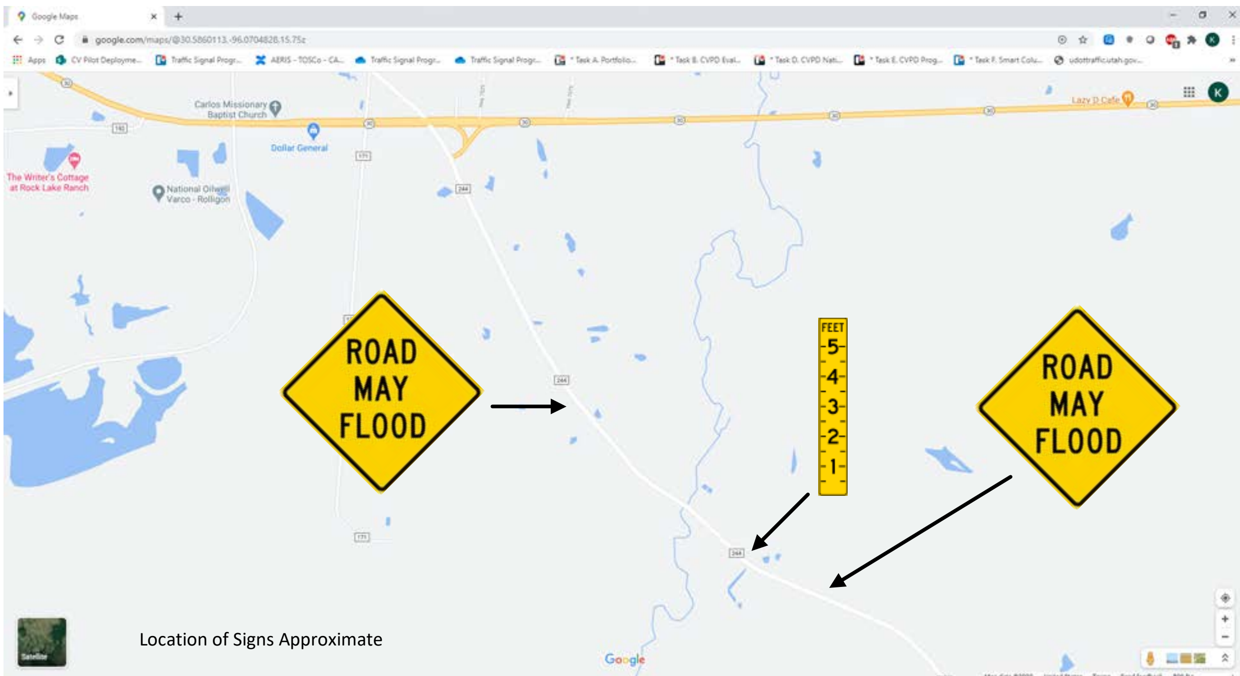


Figure 10-4. Location of Warning Signs and Flood Gauge at the FM 244 Site.

Figure 10-5 shows the enhanced striping plan proposed for this site. Figure 10-6 shows the proposed limits of installing this enhanced striping. The enhanced striping plan includes the following elements:

- Install supplemental yellow RRPMs in the centerline to decrease the spacing between the markers to 20 ft.
- Install white RRPMs on 20-ft centers on both edge lines. TxDOT may want to consider offsetting the RRPMs from the edge line by approximately 1 ft because of the high volume of motorcycle traffic in the area.

Because of the low volume of traffic on this roadway, the researchers do not propose any modifications to the existing static signing at the site.

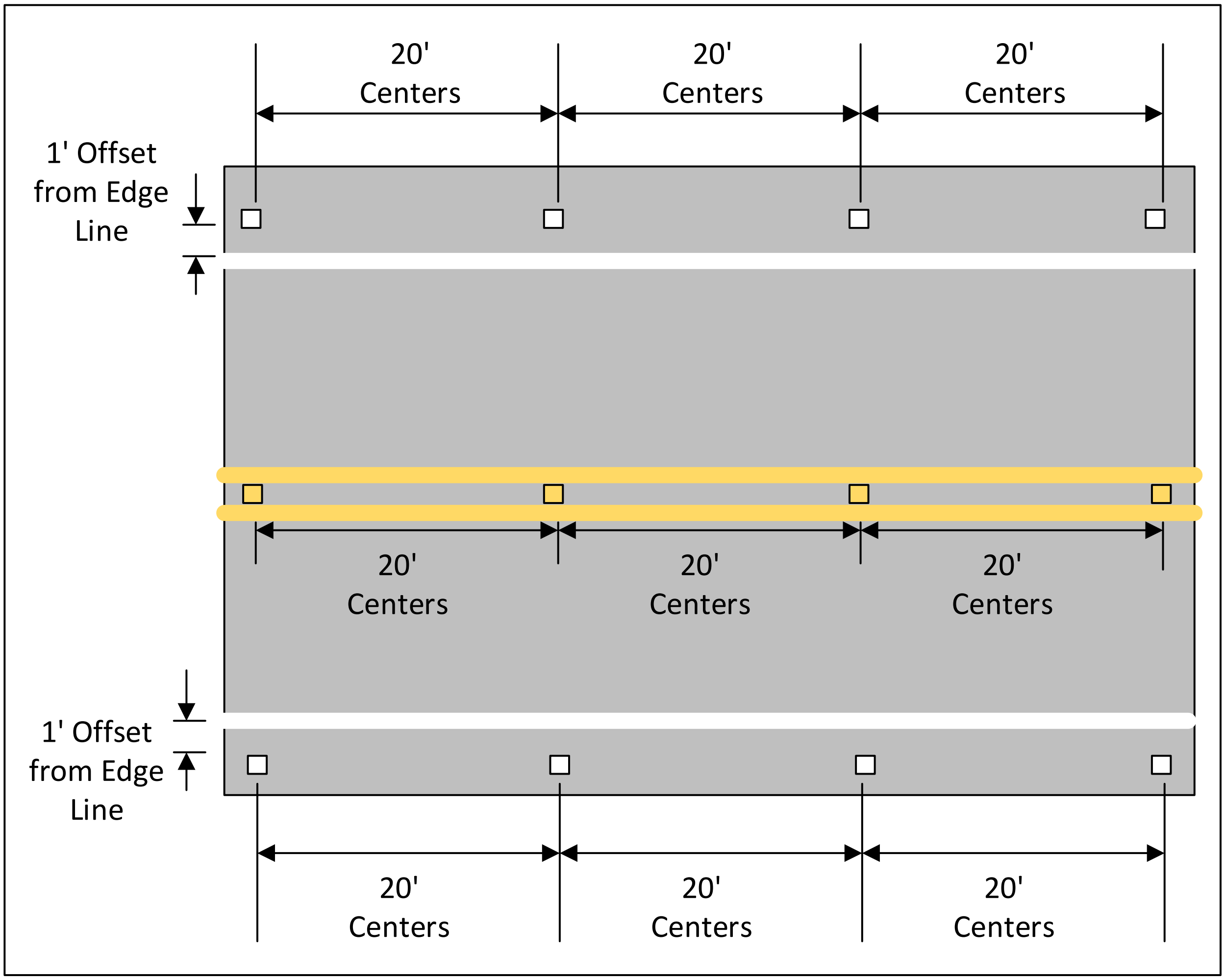


Figure 10-5. Proposed Enhanced Pavement Markings for FM 244.

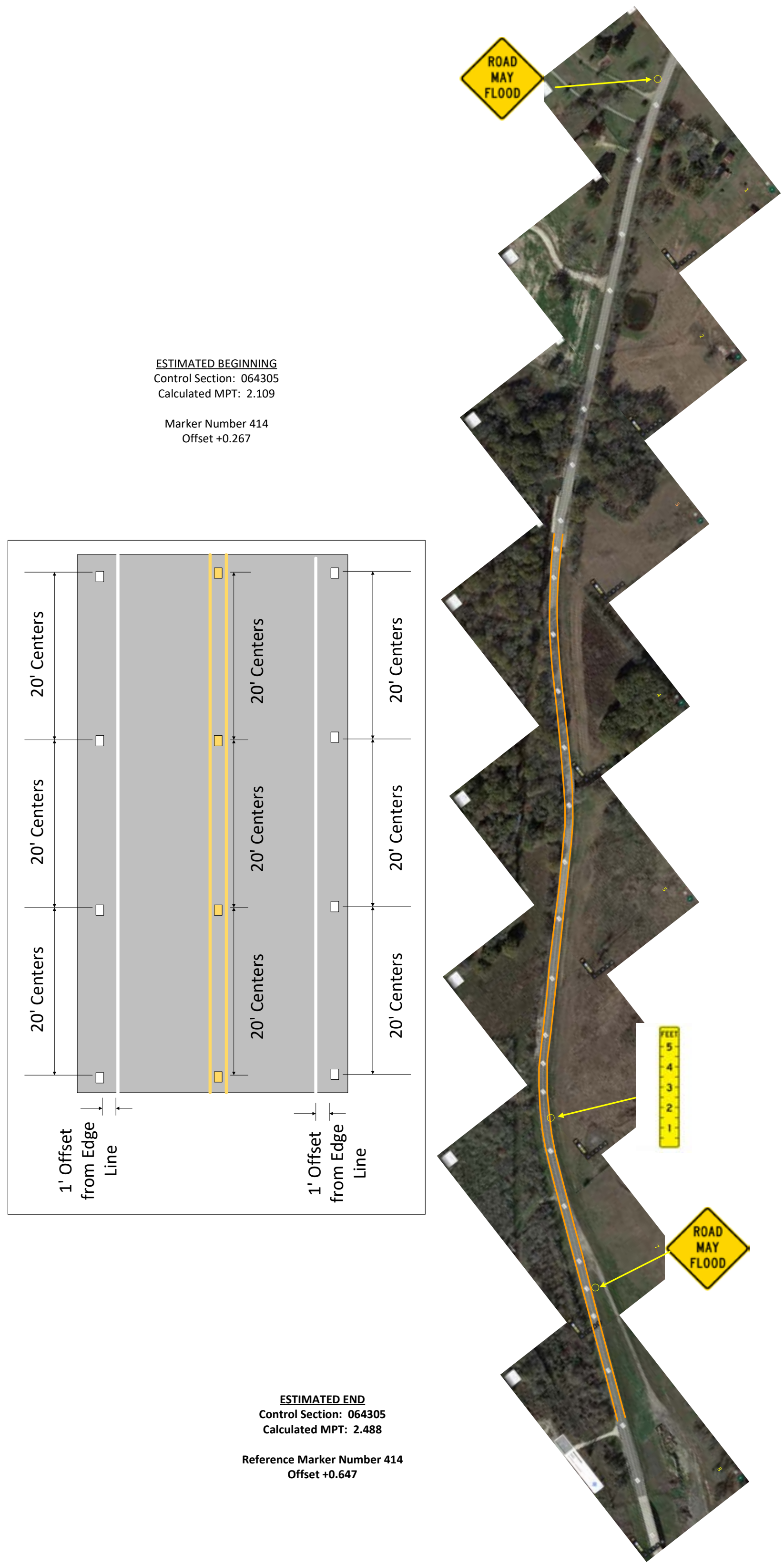


Figure 10-6. Limits of Proposed Enhanced Pavement Markings for FM 244.

10.2.1.2 FM 1179

The second site selected by the researchers as a possible candidate improvement site is located on FM 1179. FM 1179 is also a two-lane rural highway, east of Bryan–College Station. The flood area is located east of Steep Hollow over Wickson Creek. Figure 10-7 shows the LWC approaching from the west, while Figure 10-8 shows the westbound approach to the LWC. Figure 10-9 shows the current layout of the warning signs on approaches to the crossing.

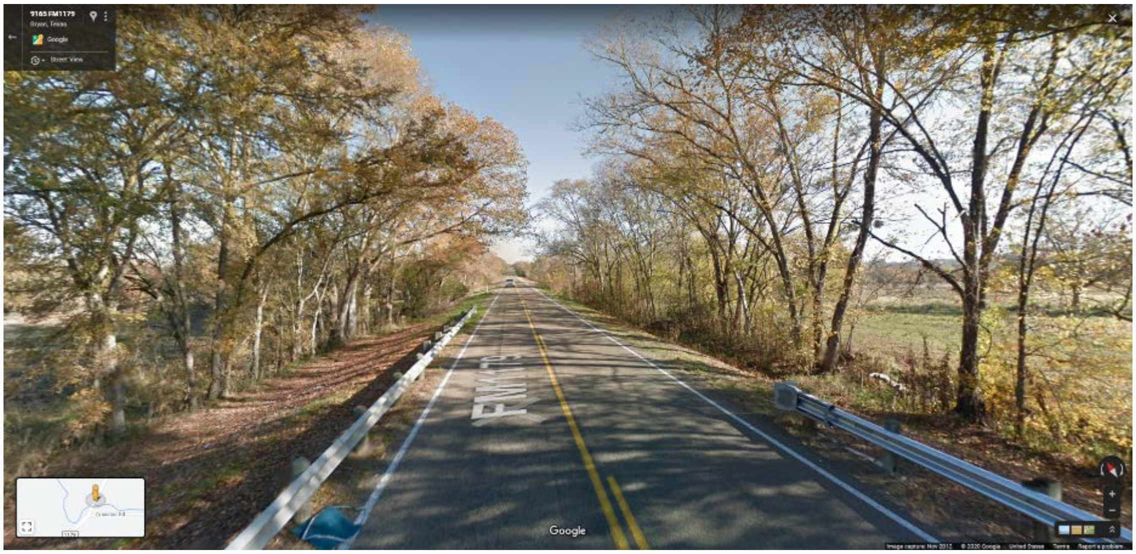


Figure 10-7. FM 1179 Eastbound, West of LWC.

Figure 10-8. FM 1179 Westbound, East of LWC.

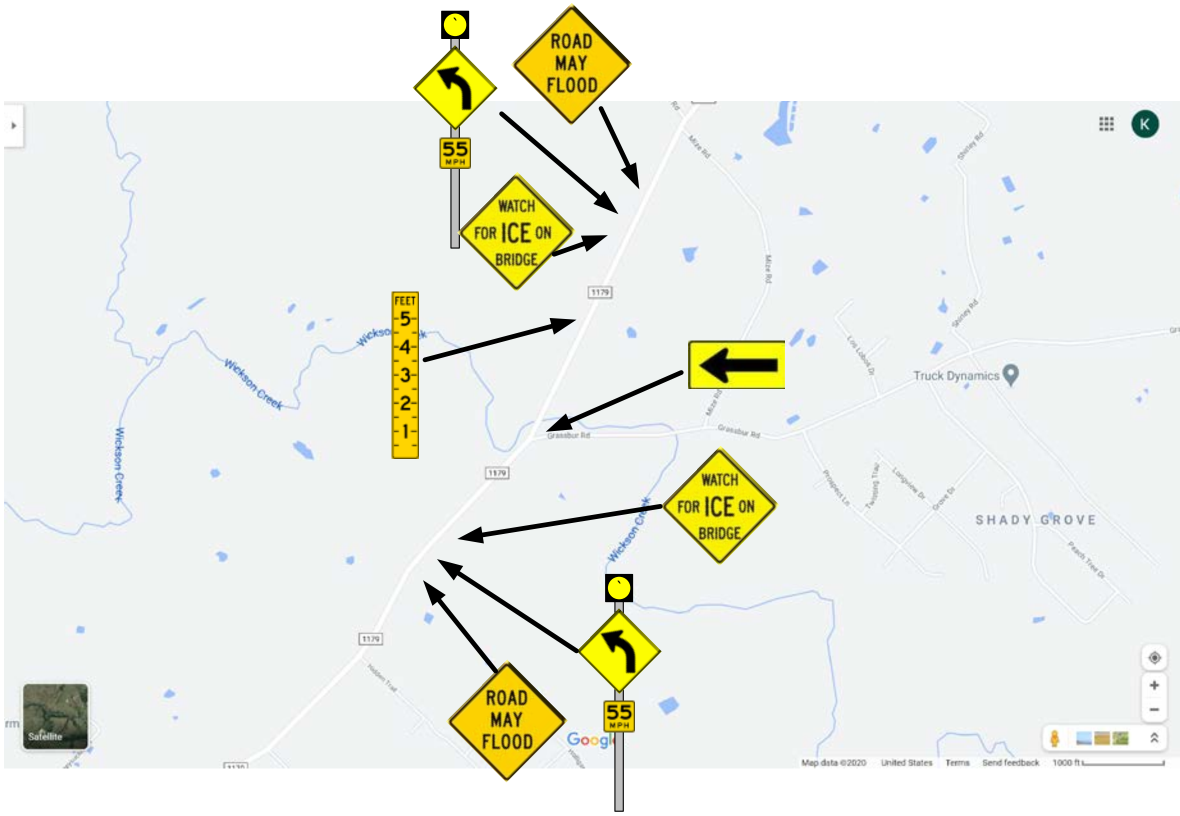


Figure 10-9. Current Layout of Advance Warning Signs for FM 1179 Crossing.

Figure 10-10 shows the enhanced striping plan proposed for this site. Figure 10-11 shows the proposed limits of installing this enhanced striping. The enhanced striping plan includes the following elements:

- Install yellow RRPMs in the centerline to maintain a 40-ft spacing between markers.
- Install white RRPMs on 20-ft centers on both edge lines. TxDOT may want to consider offsetting the RRPMs from the edge line by approximately 1 ft.

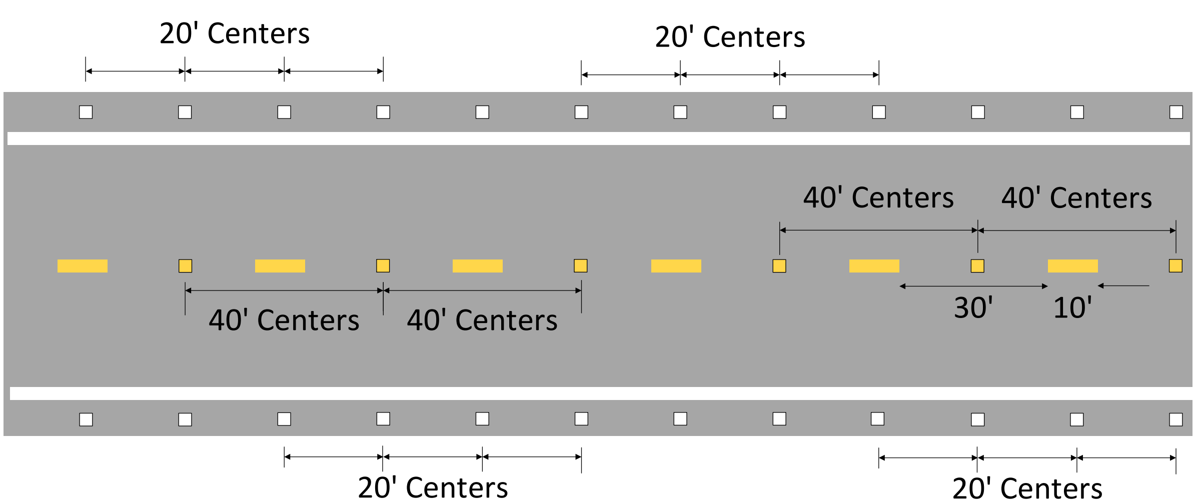


Figure 10-10. Proposed Enhanced Pavement Markings for FM 1179.

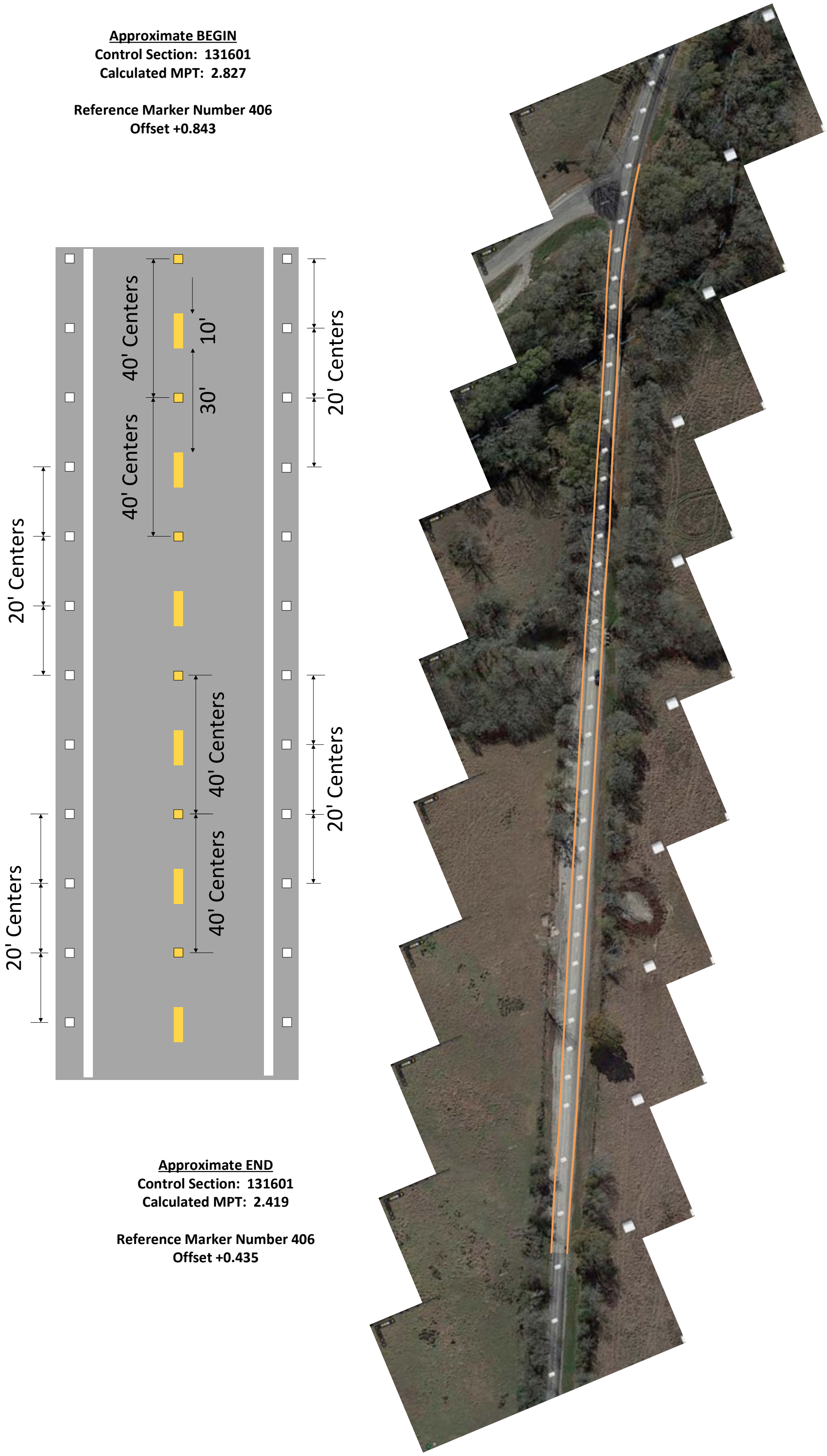


Figure 10-11. Limits of Proposed Enhanced Pavement Markings for FM 1179.

10.2.2 Beaumont District

The researchers also contacted the director of transportation operations for the Beaumont District, who identified approximately 30 locations in the district where flooding routinely occurs. The researchers conducted a preliminary review of these locations using Google Maps and identified seven potential candidates. The researchers then conducted a review of the seven sites in May 2020. The researchers identified two potential candidates for deploying enhanced delineation through the LWCs of the sites reviewed. Figure 10-12 is a site map showing the location of the two sites chosen in the Beaumont District. The following sections describe the characteristics and proposed improvements for these locations.

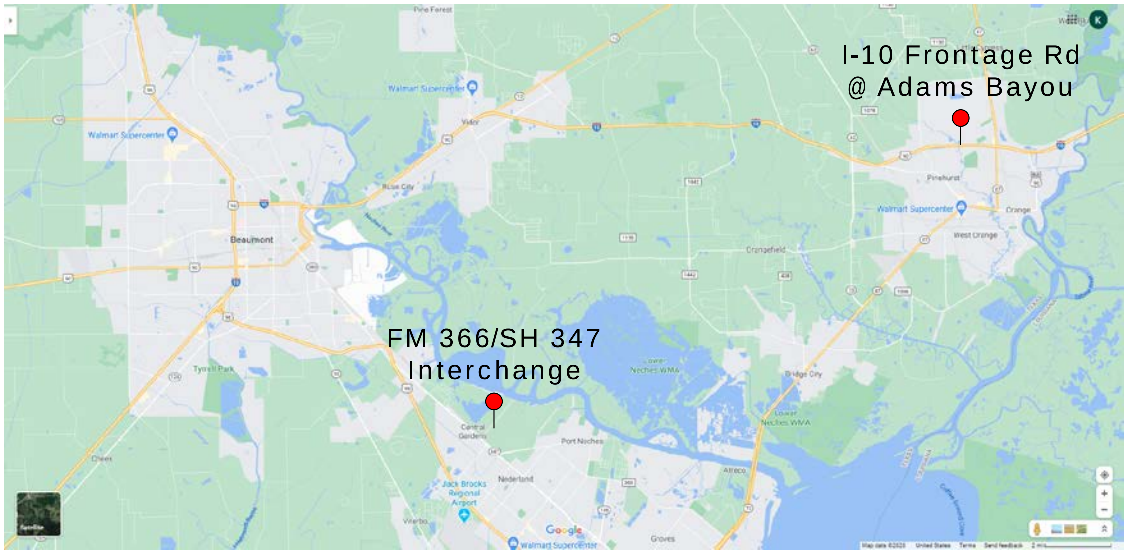


Figure 10-12. Location of Selected LWC Sites in the Beaumont District.

10.2.2.1 I-10 Frontage Road at Adams Bayou

The researchers identified the I-10 frontage road over Adams Bayou in Orange, Texas, as a potential location for enhanced treatment at the LWC. At this location, the I-10 main lanes are elevated above the two one-way frontage roads, one on each side of the main lanes. The frontage road has two lanes in each direction. U-turn lanes connect the north and south frontage roads under the I-10 main lanes. Figure 10-13 shows the south frontage road traveling in the eastbound direction, while Figure 10-14 shows the north frontage road traveling westbound. As a result of ongoing construction in the area, TxDOT has recently repaved both frontage roads.

Figure 10-13. I-10 South Frontage Road over Adams Bayou in Orange, Texas.

Figure 10-14. I-10 North Frontage Road over Adams Bayou in Orange, Texas.

Figure 10-15 and Figure 10-16 show the layout of the enhanced signing and pavement markings proposed for this LWC. Both frontage roads would receive similar treatments. The researchers propose installing RRPMs on both the edge lines at 20-ft centers. The researchers also propose installing RRPMs on the lane lines at 40-ft centers. This enhancement to the pavement markings would begin well upstream (approximately 1,500 ft) of the actual LWC. The striping arrangement would be carried over the bridge deck and extend for at least 1,000 ft beyond the bridge's end. "WATCH FOR WATER ON ROAD" signs would be replaced with "ROAD MAY FLOOD" (W8-18) warning signs. The researchers propose that TxDOT install "ROAD MAY FLOOD" warning signs on both frontage roads.

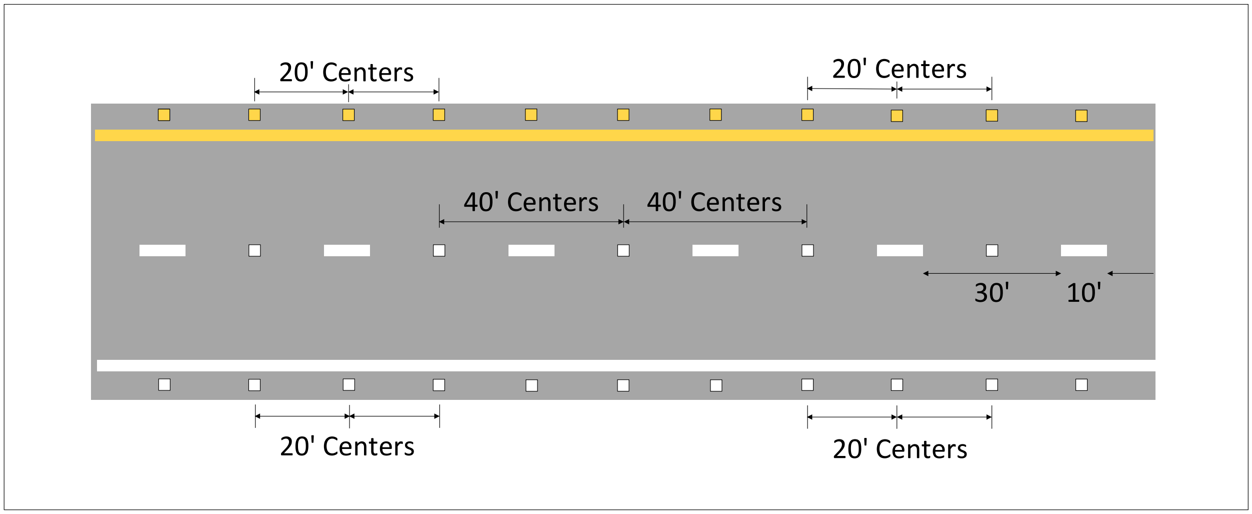


Figure 10-15. Proposed Enhanced Pavement Markings for I-10 Frontage Roads over Adams Bayou.

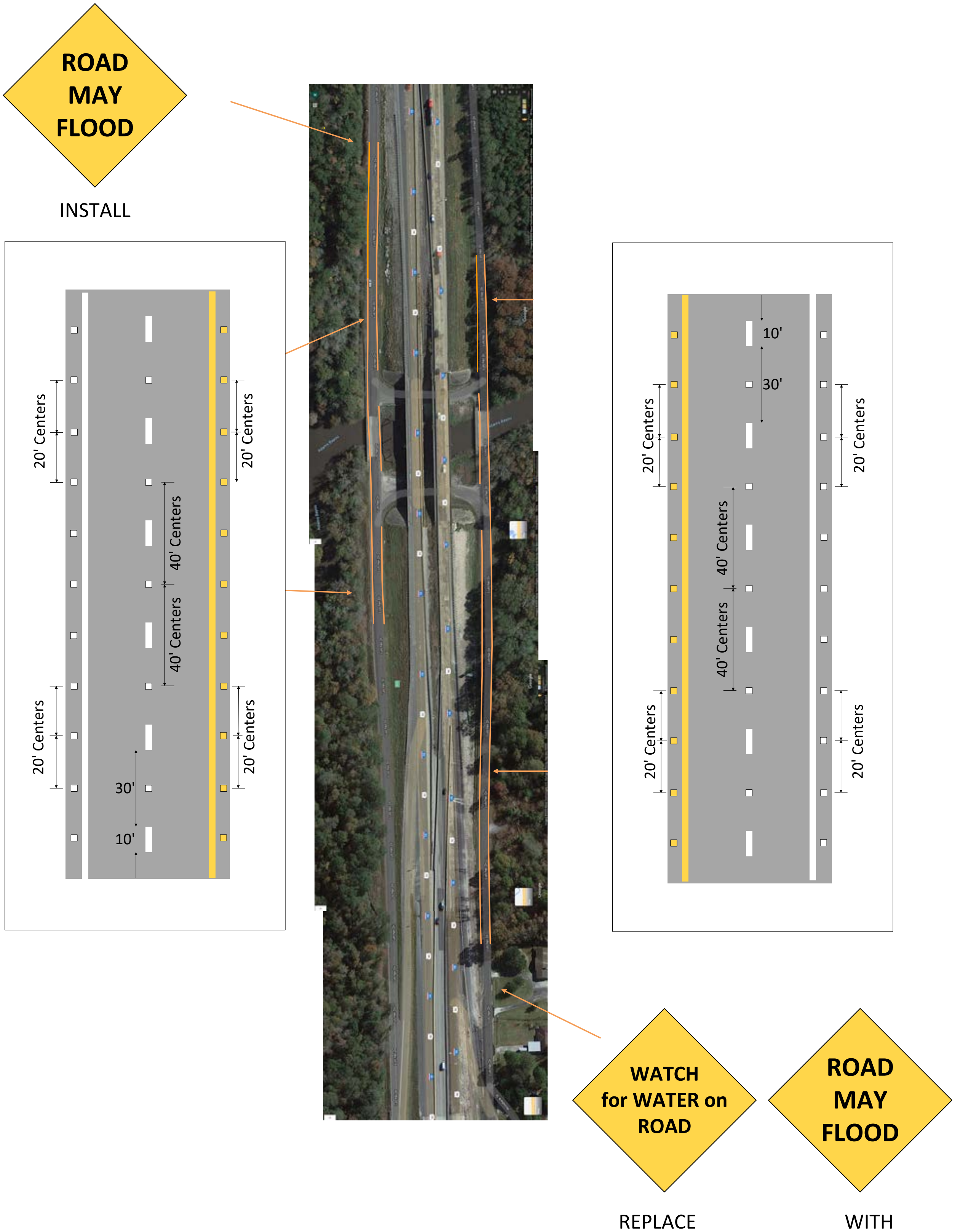


Figure 10-16. Limits of Proposed Enhanced Pavement Markings for I-10 Frontage Roads over Adams Bayou.

10.2.2.2 FM 366/SH 347 Interchange

The FM 366/SH 347 interchange in Port Neches is the researchers' last site for possible enhanced delineation. This interchange is a direct connect interchange that terminates FM 366 into SH 347. The FM 366 connection ramps travel under the SH 347 travel lanes. During heavy rains, the low point of the connecting ramps is subject to flooding. Active flood sensors exist at this location to detect when the underpasses flood. Figure 10-17 shows the placement of the warning devices on the approaches to this LWC.

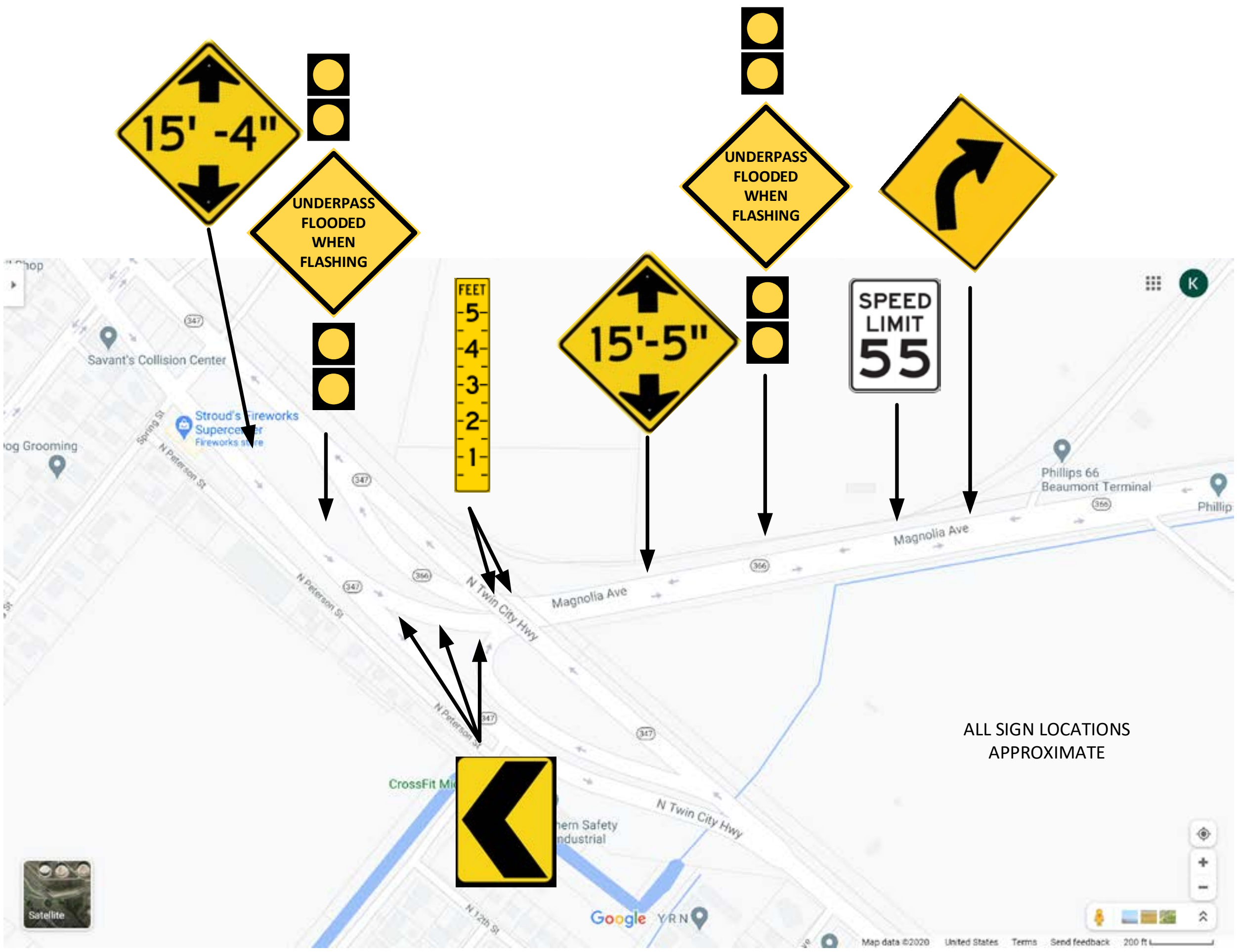


Figure 10-17. Approximate Placement of Current Warning Signs at FM 366/SH 347 Interchange.

The researchers propose two different delineation treatments, one for each direction of travel. Figure 10-18 shows the proposed delineation treatment on the southbound-to-eastbound movement. Because no lane drop exists for this movement and there is very little room to install RRPMs on the edge lines, the researchers recommend installing white RRPMs at 40-ft centers on the lane line for the southbound-to-eastbound movement.

Figure 10-19 shows the proposed enhanced delineation treatment for the westbound-to-northbound movement. The researchers propose adding yellow RRPMs to the lane-drop striping for the left side of the roadway. The researchers suggest starting the RRPMs at the beginning of the lane drop and carrying them through the LWC and up around the horizontal curve as the vehicle departs the LWC. This treatment should provide positive guidance for vehicles traversing the crossing.

Figure 10-20 shows the limits of the proposed enhanced pavement markings for the FM 366/SH 347 interchange.

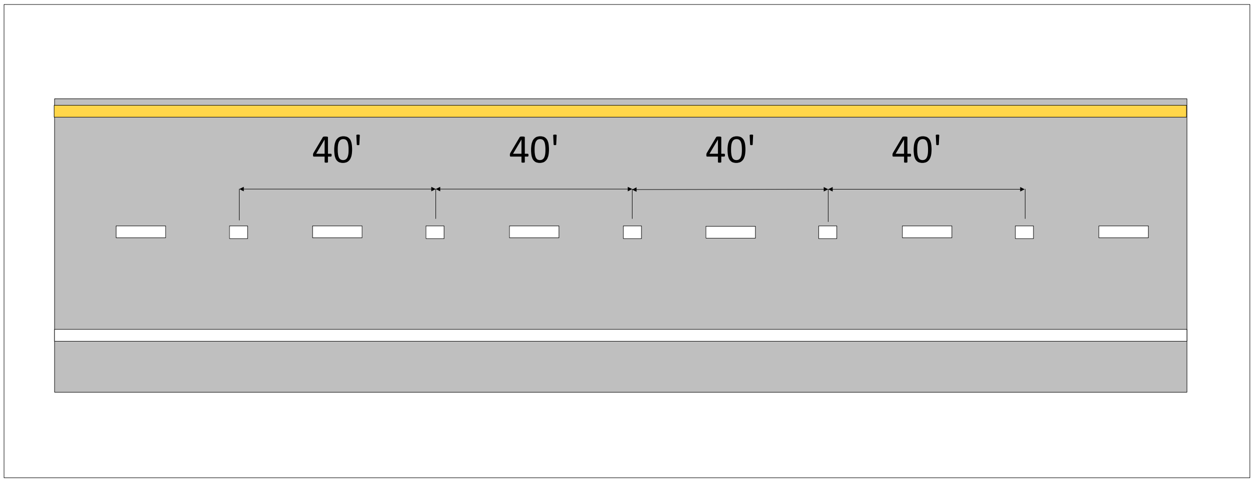


Figure 10-18. Proposed Enhanced Pavement Markings for the Southbound-to-Eastbound Movement at the FM 366/SH 347 Interchange.

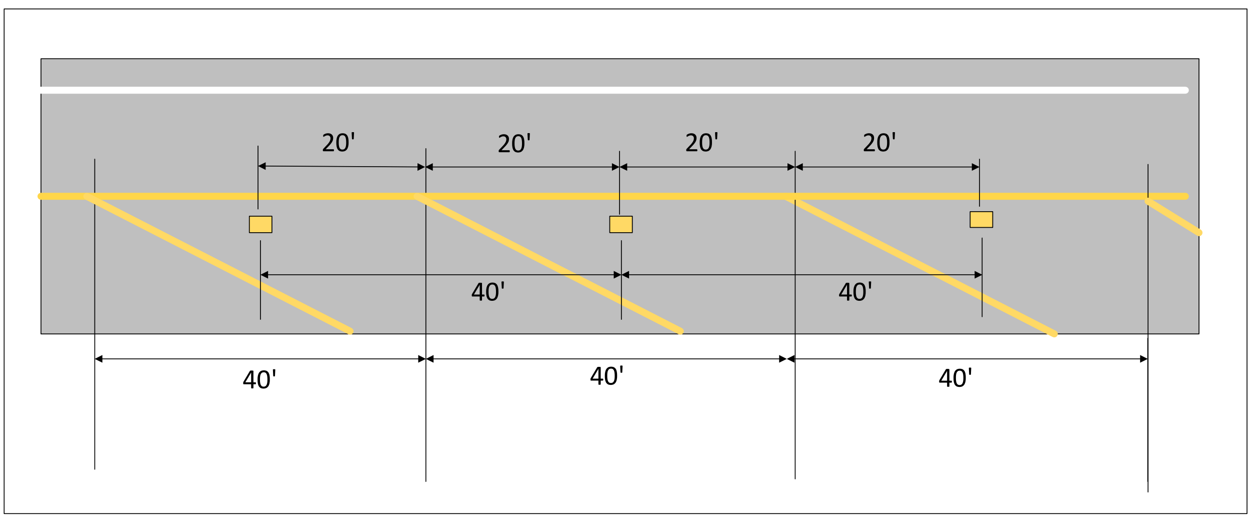


Figure 10-19. Proposed Enhanced Pavement Markings for the Westbound-to-Northbound Movement at the FM 366/SH 347 Interchange.

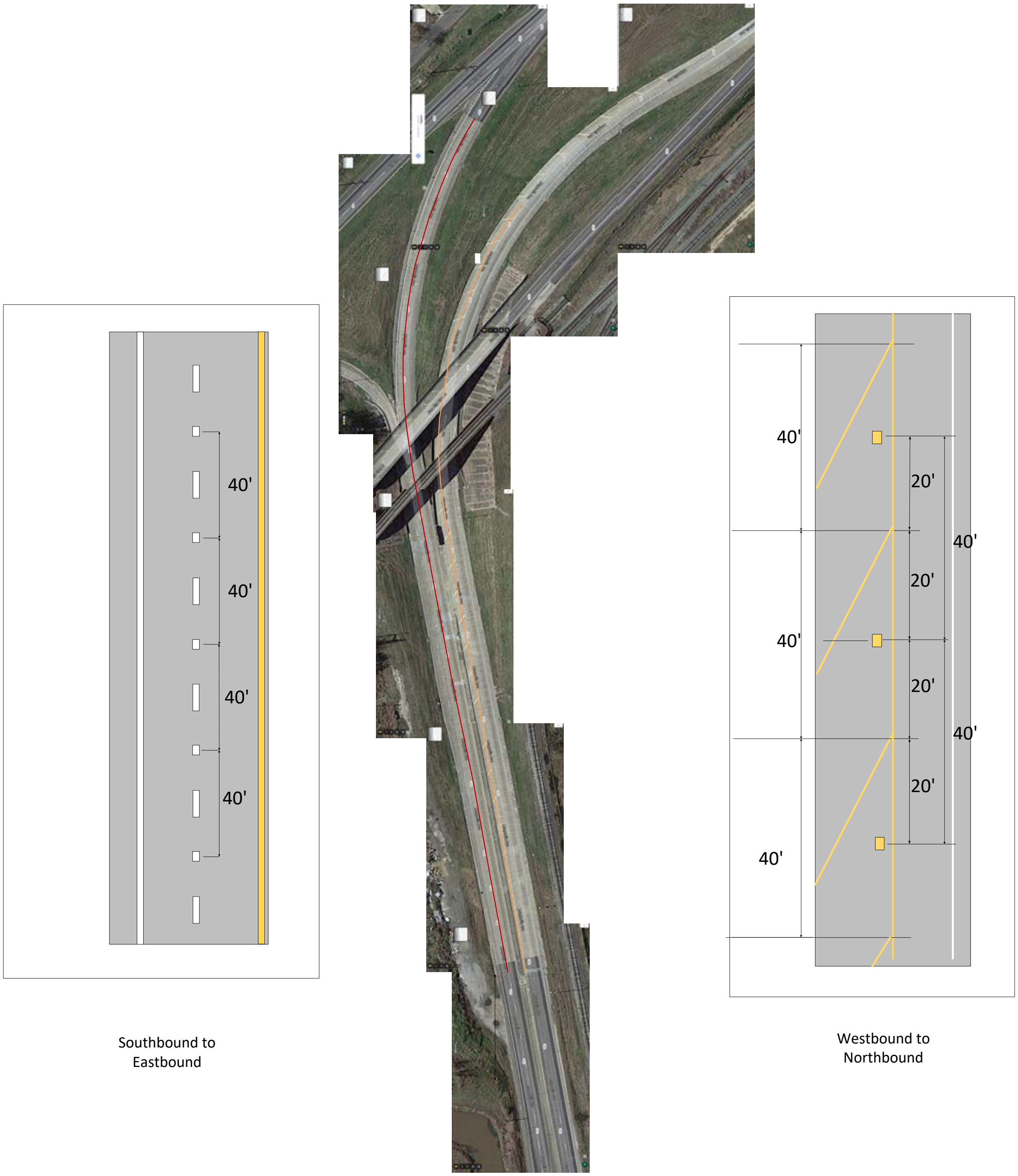


Figure 10-20. Limits of Proposed Enhanced Pavement Markings for the FM366/SH 347 Interchange.

10.3 TESTING OF PROPOSED LWC ENHANCEMENTS

Initially, the researchers planned to conduct a limited evaluation of the proposed improvements. The planned evaluation consisted of before-and-after daytime and nighttime drive-through video data collection, during both dry and wet conditions. Unfortunately, due to travel restrictions caused by the COVID-19 outbreak, the researchers were unable to collect post-deployment evaluation data at the deployment sites. The researchers will continue to work with TxDOT district staff to collect post-deployment data after implementing the proposed enhancements.

Chapter 11. IMPLEMENTATION

11.1 INTRODUCTION

As part of this project, the researchers explored how TxDOT might use easy, low-cost countermeasures to improve safety at LWCs. Countermeasures focused on enhancing delineation techniques, improving flood detection sensors, deploying active and passive warning devices, and integrating CV technologies to increase driver awareness of LWCs. The researchers used the results of this implementation to propose improvements at four LWCs in Texas. This chapter summarizes the prominent findings and outcomes associated with this research project.

11.2 SUMMARY OF FINDINGS AND CONCLUSIONS

The following provides a summary of the findings and conclusions identified through this research project:

- The researchers conducted a comprehensive review of literature related to LWCs. The literate review found that many states do not encourage LWCs unless the traffic volume is very low on those roadways. Only a handful of studies have examined different risk factors and countermeasures associated with LWCs. The literature shows that, in general, past works supports the notion that LWCs are low-cost solutions for roadways with low traffic volume. Additionally, other states have successfully implemented several countermeasures and design alternatives that TxDOT may consider implementing.
- The researchers surveyed both TxDOT area offices and other state DOTs concerning practices related to LWCs. The researchers found that most agencies do not maintain a comprehensive inventory of LWCs. More than half of the agencies apply consistent countermeasures across all LWCs. Instead, agencies develop and implement countermeasures on a site-by-site basis, explicitly tailored to the needs of the LWC. Most agencies report that barricades and static signs are common countermeasures.
- The researchers also examined the use of multiple databases to help TxDOT prioritize LWCs for potential improvements. These databases included TxDOT's CRIS and RHiNO, the LWC Database from HCRS, and the LWC Database from TNRIS. The researchers showed how TxDOT could potentially mine these databases to identify high-priority roadway segments that require attention. The research effort showed that every year, around 2,885 crashes occur on Texas roadways where standing water exists. Approximately 27 percent of these crashes involve a fatality or injury. The research effort also found that the majority of LWC segment-related crashes occur on minor arterials and major collector roadways.
- The researchers investigated marking or marker treatment strategies for improving delineation at LWCs. The delineation treatment objectives were to provide long-range warning of flooded roadway conditions at night while also providing adequate short-range visibility to help motorists not enter the LWC during flooded conditions at both day and night. The researchers conducted a photometric evaluation of different types of marking and marker treatments under various water depths and turbidity levels. The testing indicated both the markings and RRPMs lose their conspicuity when

covered with water. To achieve long-range warning of flooded roadway conditions at night, the researchers recommend the following treatments:
    - TxDOT should apply RRPMs at a minimum of 500 ft outside of the potential flooded area on either side.
    - For two-lane two-way roads, TxDOT should use yellow RRPMs along the centerline area.
    - For multilane undivided highways, TxDOT should apply yellow and white RRPMs along the centerline and lane line, respectively.
    - For divided highways, TxDOT should implement white RRPMs on the lanes.
    - Spacing of the RRPMs should be the minimum allowable for the roadway type and marking configuration. This minimum spacing would offer the greatest visibility of the flooded condition by providing a more continuous line of RRPMs that would then be broken by the flooded condition.
    - At problematic locations, RRPMs could be used along the edge line markings to provide additional warning and guidance.
- The researchers suggest that TxDOT consider using IIRPMs at problematic locations where drivers regularly drive through high-water conditions and drive off the roadway. TxDOT may want to consider installing yellow IIRPMs to improve delineation of the centerline of the roadway. In conjunction with an active warning system for flooded conditions, TxDOT may want to consider using red IIRPMs and signing to indicate a stop-and-turn-around condition. This application would be limited to problematic areas due to the added costs compared to standard markings and RRPMs. This red IIRPM setup would require a request for experimentation from FHWA.
- The researchers identified five different types of sensors commonly deployed by state DOTs to measure water levels: pressure sensors, float sensors, bubbler sensors, ultrasonic sensors, and radar sensors. The researchers developed an experimental study of flood sensors and warning devices to ascertain their ability to measure the water level in flooding conditions and LWCs. The researchers tested five sensors, including both non-contact and submersible devices, under dissimilar local and environmental conditions. The following observations were noted:
    - Ultrasonic sensors performed very well during the experimental tests. The sensors could measure the water level in different environments, although the devices failed to detect the level of water with extreme foam. Debris in the water produced some errors.
    - Radar-based sensors predicted the level of pure water with good accuracy, but their performance in measuring the water depth in poor water conditions was not as good as the other devices. Researchers observed some errors in the device measurements when tested with foam and debris. However, the reasonable cost and the ease of use on site may compensate for this lack of robustness.
    - The pressure sensor registered the most accurate results in any condition. The sensor measured up to 11 ft, and its cost is still acceptable. Nonetheless, the researchers noted concerns about installation and durability with minimal maintenance.

- The researchers designed, built, and tested a prototype system for providing alerts and warnings at LWCs using CV technology. They examined the application of appropriate I2V and I2I technologies for providing flood condition reports at LWCs in a CV environment. The researchers considered two different architectures: one integrated with TxDOT's LoneStar Traffic Management System software and another designed as a standalone system for deployment at an isolated LWC. Proof-of-concept testing at the Texas A&M University System RELLIS Campus demonstrated that the applications could provide advanced warnings and alerts to drivers directly in their vehicles.

11.3 GUIDELINE FOR ENHANCING DELINEATION AT TXDOT LWCS

The most critical condition addressed in this study is the flooded roadway condition at night. Drivers may not be able to see the water across the roadway in time to stop safely due to the lack of ambient lighting, lack of warning systems, and/or lack of familiarity with roadway conditions. Tests conducted by TTI indicated that both the markings and RRPMs evaluated lose visibility when covered with water. Limited visibility of the pavement marking might provide additional positive guidance that the road is covered with water. The visibility of pavement markings is generally limited to within 500 ft under low-beam illumination. RRPMs can be used to provide much longer detection distances.

For long-range warning of the flooded roadway condition at night, the researchers recommend the following.

- *Apply RRPMs to the centerline and lane lines through the areas where flooding conditions may occur*. RRPMs should be carried a minimum of 500 ft outside the potential flooded area. The roadway configuration should govern the type of RRPM used as follows:
    - For two-lane two-way roads, yellow RRPMs should be used along the centerline area (see Figure 11-1).
    - For multilane undivided highways, yellow centerline and white lane line RRPMs should be implemented (see Figure 11-2).
    - For divided highways, white lane line RRPMs should be implemented (see Figure 11-3).
- *Use the minimum allowable spacing* on the RRPMs for the roadway type and marking configuration.
- *At problematic locations, use RRPMs along the edge line markings* to provide additional warning and guidance.

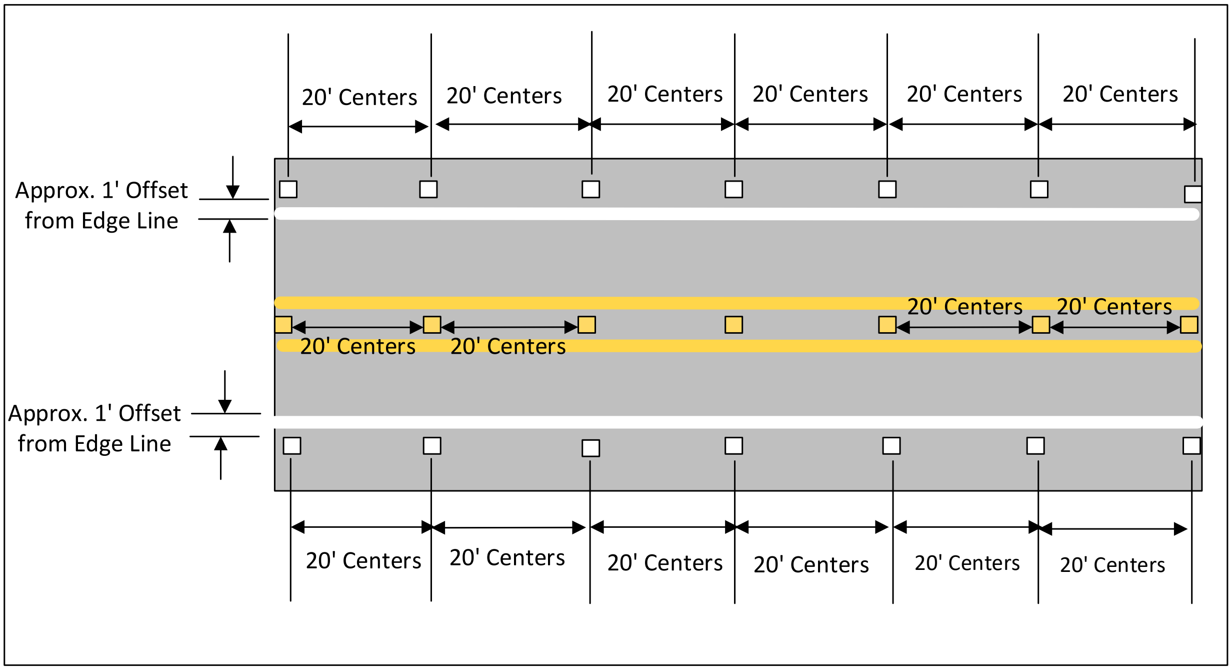


Figure 11-1. Recommended RRPM Spacing and Placement for LWCs and Flood-Prone Areas on Two-Lane Highways.

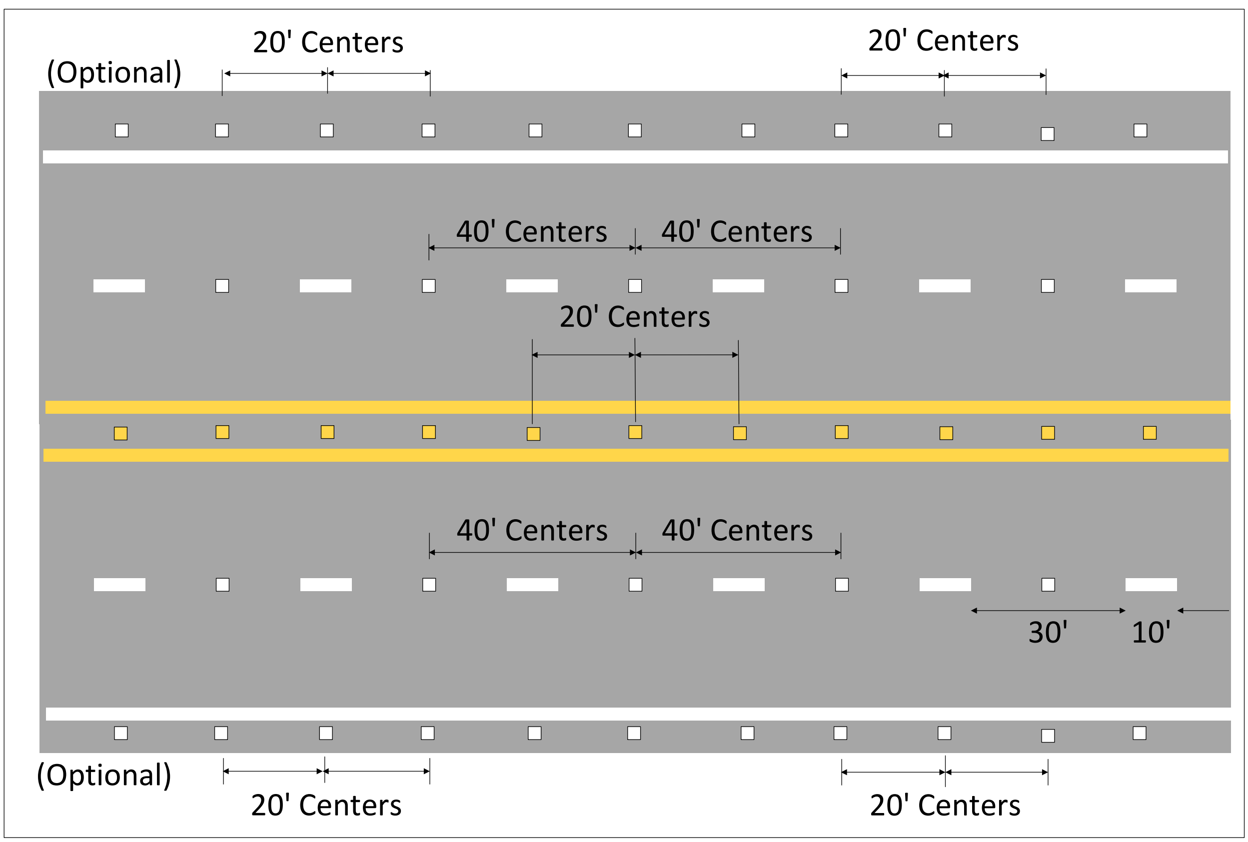


Figure 11-2. Recommended RRPM Spacing and Placement for LWCs and Flood-Prone Areas on Undivided Multilane Highways.

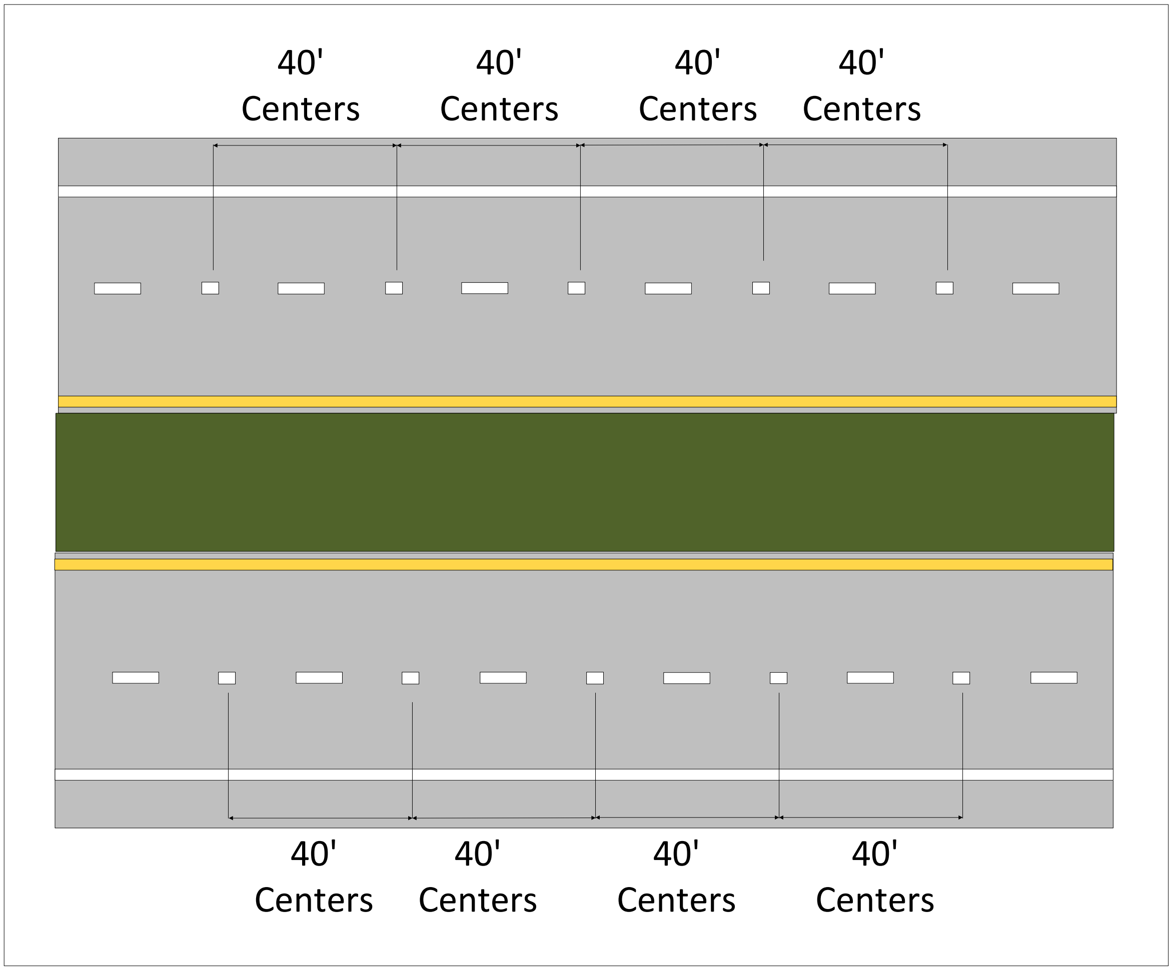


Figure 11-3. Recommended RRPM Spacing and Placement for LWCs and Flood-Prone Areas on Divided Multilane Highways.

Other suggested improvements include the following:

- *Use both white and yellow standard pavement markings throughout the same areas in which the RRPMs would be implemented*. These markings will help guide motorists through the LWC area when the water is shallow. At night and in deeper water situations during the day, these markings will be less visible or not visible at all and thus may serve as a deterrent to enter the water because of the lack of visibility.
- *Use traditional pavement marking materials.* The researchers did not find any benefit to utilizing more expensive preformed tape or wet-weather pavement marking systems over traditional paint markings in flooded conditions.
- *Consider using IIRPMs at problematic locations* where drivers regularly drive through high-water conditions and drive off the roadway. Yellow IIRPMs could be implemented to improve delineation of the centerline of the roadway. In conjunction with an active warning system for flooded conditions, red IIRPMs and signing could be used to indicate a stop-and-turn-around condition due to flooding. The red IIRPMs could be placed across the lane and activated automatically when flooded conditions limit the safe passage of the roadway. This type of setup should be limited to

problematic areas due to the added costs compared to standard markings and RRPMs. Using the red IIRPM in the manner suggested requires a request for experimentation from FHWA.

11.4 VALUE OF RESEARCH

Following the procedures outlined in TxDOT's University Handbook, the researchers assessed the potential value of TxDOT Research Project 0-6992: Traffic Safety Improvements at Low Water Crossings. Table 11-1 shows the areas where this research project would be expected to generate benefits for TxDOT.

The value of research assessment included qualitative and economic assessments of the potential benefits. This section presents the findings from the research team's value of research assessment.

11.4.1 Qualitative Benefits

The researchers identified the following qualitative benefits associated with the outcomes of this research project:

- Improved safety.
- Increased level of knowledge by TxDOT personnel on the issues and technologies for use at LWCs.
- Increased quality of life for Texas motorists and TxDOT personnel.
- Improved customer satisfaction.
- Use of intelligent transportation system (ITS) technologies.

Table 11-1. Potential Benefit Areas Associated with Project 0-6992.

Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both	Definition in context to the Project Statement
Level of Knowledge	X			X			Will aid in better understanding flood events and potentially assist with prioritizing response
Quality of Life	X			X			Will aid in eliminating wasted time for motorists and TxDOT personnel responding to the flooded roadway
Customer Satisfaction	X			X			Will improve the Department's current flooded roadway practices while being cost conscious. Clearer and more accurate public recognition of the hazards at low water crossings could improve customer satisfaction.
System Reliability		X		X			Will aid in providing more consistent and efficient response to flooded roadways
Intelligent Transportation Systems		X				X	Will potentially provide capabilities to measure floodwaters to establish history, assist in forecasting, ITS, and share information with the travelling public
Engineering Design Improvement			X			X	The research may identify some applicable improvements to our current designs.
Safety			X			X	Will improve methods to prevent motorists from driving into flooded roadways thus resulting in fewer lives lost

Source: Texas A&M Transportation Institute.

The following subsections provide a summary of the benefits identified by the researchers.

11.4.1.1 Improved Safety

Improving safety is perhaps the most significant benefit of this research. Texas leads the nation in flood-related motor vehicle deaths. This research provides TxDOT with strategies and techniques to increase the conspicuity and awareness of water in LWCs. This research offers strategies for improving striping delineation through LWCs. The research also demonstrates the use of advanced traveler information systems to issue flood warnings and alerts directly to motorists in their vehicles. These strategies and techniques are all designed to discourage motorists from entering flooded grade crossings, resulting in lives saved.

11.4.1.2 Level of Knowledge

One of the primary benefits of this research project is the increased level of knowledge of TxDOT personnel related to the issues and potential solutions for improving safety at LWCs on TxDOT highways. Project findings enhance TxDOT personnel's knowledge of where flooding events are likely to occur on TxDOT-maintained facilities. The research provides TxDOT personnel with strategies and techniques for detecting flooded roadways and improving delineation on flood-prone roads. The study results show TxDOT personnel how TxDOT could integrate its existing flood sensor technologies with advanced vehicle notification systems to disseminate flood warnings and alerts to drivers in their vehicles.

11.4.1.3 Quality of Life

The research has the potential to improve the quality of life for Texas motor vehicle operators. A fundamental premise of this research was that motorists could receive notifications about roadways experiencing flooding farther in advance of the crossing where diversion opportunities exist through better delineation techniques and advanced technologies. By receiving messages farther in advance of flooded crossings, motorists can seek alternate routes around the flooded crossing, reducing driver frustration, improving decision-making, and reducing wasted time.

11.4.1.4 Customer Satisfaction

This research also has the potential to improve customer satisfaction with TxDOT. TxDOT can use the results of this research to improve the current delineation and motorist notification practices at LWCs and flood-prone areas. The public benefits from more precise and accurate information about the status of the hazards associated with flooded crossings.

The research project revealed strategies for increasing the conspicuity of the pavement edge at LWCs. Drivers at night may not be able to see the water across the roadway in time to stop safely due to a lack of ambient lighting, absence of warning systems, and failure to travel consistent with roadway conditions. This research provides strategies and techniques that TxDOT can use to assist drivers in assessing whether an LWC is passable.

11.4.1.5 Intelligent Transportation Systems

This research illustrates the value of TxDOT's use of ITS technologies. As part of this research, the researchers developed an advanced traveler information system that expanded on current ITS technologies used by TxDOT, including the TxDOT LoneStar Traffic Management System and the current automated flood sensor system used by many TxDOT districts.

Detection of dangerous conditions is the first step toward safety improvements. The detection of hazardous water crossings is supported through LoneStar's integration with a wide variety of water sensors. TxDOT can detect water conditions reliably and repeatedly by utilizing and deploying hardened commercial sensors.

The project also demonstrates how TxDOT could integrate these water detection systems with I2I and I2V technologies for disseminating warnings and alerts to drivers directly in their vehicle. Integrated solutions using CV technology can provide alerts to drivers who are on a roadway that is affected by an LWC. Additionally, TxDOT can give the travelers warnings farther in advance of the crossings, allowing them to take a detour or alternative route. By utilizing direct communication through DSRC or C-V2X technology, drivers can be alerted directly by the DOT. Alternatively, third-party companies can provide information to drivers through C2C or standardized data fields provided by data portals. By leveraging the connectivity of travelers, TxDOT can provide advanced alerts to CVs and lower the occurrence of drivers entering dangerous LWCs.

11.4.2 Economic Assessment

The researchers conducted an economic assessment of the benefits associated with the outcomes of this research project. The researchers identified two functional areas where TxDOT may benefit from this research: safety and ITSs.

The researchers identified the following two potential safety benefits as an outcome of this research effort:

- Reduction in the number of vehicles getting swept away in LWCs.
- Reduction in the number of swift-water rescues performed by emergency responders.

The researchers also included the increased level of ITS device maintenance and enhanced delineation as a potential negative benefit associated with this project. The researchers did not identify any quantifiable system reliability or engineering design improvement benefit associated with the outcome of this research study.

The following subsections provide a summary of the data and assumptions used to compute the economic value of this research project.

11.4.2.1 Reduction in Crashes in LWCs

Table 11-2 lists the severity types of the crashes that occurred on 10 TxDOT roadways with LWCs. The researchers assumed that 0.1 percent of those crashes listed in Table 11-2 were addressable by the strategies identified in this research to estimate benefits associated with reducing crashes at flooded LWCs. The researchers developed the following potential reductions in crash types because of this research:

- Fatalities (K) = 0.0692/year.
- Incapacitating injuries (A) = 0.4328/year.
- Non-incapacitating injuries (B) = 1.77356/year.
- Complaint of injuries (C) = 2.7126/year.
- Unknown injury (O) = 9.168/year.

Table 11-2. Number of Crashes Occurring in LWCs on 10 Representative TxDOT Roadways.

Year	Fatal (K)	Incapacitating (A)	Non-incapacitating (B)	Complaint (C)	Unknown Injury (O)
2013	65	372	1,681	2,414	7,876
2014	70	429	1,626	2,571	8,410
2015	74	424	1,724	2,740	9,508
2016	68	450	1,835	3,072	10,112
2017	69	489	1,812	2,791	9,934
Average	69.2	432.8	1,735.6	2,717.6	9,168

Source: Texas A&M Transportation Institute.

Figure 11-4 shows the value of reduced fatality data recommended by the U.S. Department of Transportation for estimating the value of reducing crashes of certain types. These values are in 2017 dollars. The researchers adjusted to 2020 dollars using standard inflation rates based on the Consumer Price Index. After making this conversion, the researchers estimated the potential cost savings caused by reducing collisions at LWCs. Table 11-3 shows the results of the potential benefits associated with enhancing safety at flooded LWCs.

Recommended Monetized Value(s)				References and Notes
MAIS Level	**Severity**	**Fraction of VSL**	**Unit value ($2017)**	*Guidance on Treatment of the Economic Value of a Statistical Life in U.S. Department of Transportation Analyses (2016)* https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-on-valuation-of-a-statistical-life-in-economic-analysis
MAIS 1	Minor	0.003	$28,800	
MAIS 2	Moderate	0.047	$451,200	
MAIS 3	Serious	0.105	$1,008,000	
MAIS 4	Severe	0.266	$2,553,600	
MAIS 5	Critical	0.593	$5,692,800	
Fatal	Not Survivable	1.000	$9,600,000	

KABCO Level	Monetized Value
O – No Injury	$3,200
C – Possible Injury	$63,900
B – Non-incapacitating	$125,000
A – Incapacitating	$459,100
K – Killed	$9,600,000
U – Injured (Severity Unknown)	$174,000
# Accidents Reported (Unknown if Injured)	$132,200

Note:
The KABCO level values shown result from multiplying the KABCO-level accident's associated MAIS-level probabilities by the recommended unit Value of Injuries given in the MAIS level table, and then summing the products. Accident data may not be presented on an annual basis when it is provided to applicants (i.e. an available report requested in Fall 2011 may record total accidents from 2005-2010). For the purposes of the BCA, is important to annualize data when possible.

Source: (*81*)

Figure 11-4. Estimated Cost of Collisions, by Collision Severity.

Table 11-3. Estimates of Potential Crash Reduction Benefits.

Crash Type	Estimated # of Crashes	Cost per Crash Type (2017)	Cost per Crash Type (2020)	Value of Research
Fatality (K)	0.0692	$9,600,000	$10,217,999	$707,086
Incapacity Injury (A)	0.4328	$459,100	$488,655	$211,490
Non-incapacitating Injury (B)	1.7356	$125,000	$133,046.86	$230,920
Possible Injury (C)	2.7176	$63,900	$68,013.56	$184,835
No Injury (O)	9.168	$3,200	$3,406	$31,226
			TOTAL	**$1,365,556**

Source: Texas A&M Transportation Institute.

11.4.2.2 Reductions in Swift-Water Rescues

The researchers also envision that, if implemented, the enhanced delineation and improved traveler warnings and alerts would reduce the number of swift-water rescues that emergency responders have to perform. The number of swift-water rescues performed annually in Texas is not easily attainable. Furthermore, the costs associated vary depending on the following factors:

- The type of equipment that emergency responders use to perform the rescue (e.g., boat, ladder truck, aircraft, etc.).
- The nature of the extraction.
- The extent of the search area.
- The number of individuals rescued.
- The duration of the rescue.

The researchers assumed the average cost of a swift-water rescue to be $15,000. The researchers assumed that the enhanced delineation and improved warnings and alerts associated with the advance traveler information system might reduce the number of swift-water rescues by 10 per year across the state. This reduction in swift-water rescues would result in an estimated net benefit of $150,000 per year.

11.4.2.3 Increased Maintenance Costs

To be effective, TxDOT needs to maintain its devices and enhanced delineation strategies in a state of good repair. The need for increased maintenance of devices represents a cost (or negative benefit) to TxDOT. The researchers assumed that deploying some of the strategies developed in this research places an additional burden on TxDOT district maintenance and operations resources. The researchers included these negative benefits in the economic assessment. While the exact maintenance costs depend on the types of strategies deployed at each crossing, the researchers estimated that the need to support the enhanced delineation strategies and advanced ITS technologies would cost each district an additional $50,000 per year. Conservatively, this cost was applied to all 25 districts, resulting in a $1,250,000 negative benefit to TxDOT annually.

11.4.2.4 Expected Value Duration

Advanced technologies, particularly ITS technologies, have a relatively short life cycle. Most advanced technologies have a general life cycle of approximately seven years, at which time new product lines are announced and begin to filter into deployment. TxDOT's general practice is to phase new technological advances into deployment over several years; therefore, the researchers assumed a 10-year life cycle with the benefits of this research aggregated over this time.

11.4.2.5 Value of Research Computation

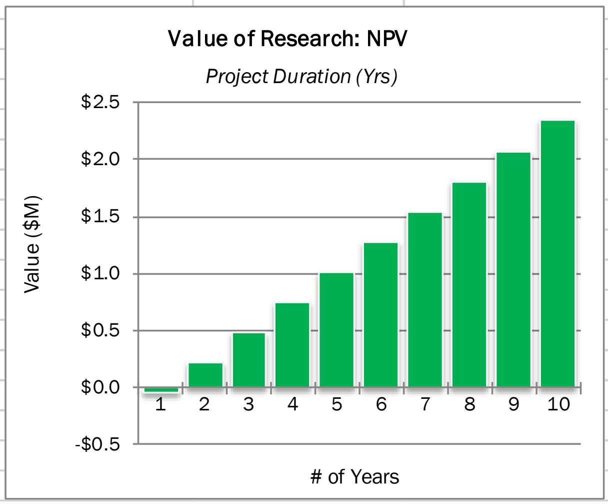
Using these estimates of the value of research, the researchers computed the value of this research. The researchers used TxDOT's value of research computational spreadsheets.

Figure 11-5 shows the results of the return on investment of this research to TxDOT. From this information, the researchers concluded the following:

- This research project has a benefit-cost ratio of 4.
- The payback period for this research project is 2.4 years.
- After 2.4 years, this research has the potential to net TxDOT $265,556 in value annually.

Texas Department of Transportation	Project #	0-6992		
	Project Name:	Traffic Safety Improvements at Low Water Crossings		
	Agency:		Project Budget	$ 581,348
	Project Duration (Yrs)	2.3	Exp. Value (per Yr)	$ 265,556
Expected Value Duration (Yrs)		10	Discount Rate	0%
Economic Value				
Total Savings:	$ 1,758,423	Net Present Value (NPV):		$ 2,339,771
Payback Period (Yrs):	2.189170	Cost Benefit Ratio (CBR, $1 : $___):		$ 4

Years	Expected Value
0	$0
1	-$50,235
2	$265,556
3	$265,556
4	$265,556
5	$265,556
6	$265,556
7	$265,556
8	$265,556
9	$265,556
10	$265,556



Source: Texas A&M Transportation Institute

Figure 11-5. Results of Value of Research Computations.

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APPENDIX A. STATE-OF-THE-PRACTICE SURVEY QUESTIONS

Question 1: Contact information.

Question 2: Does your Area Office have an inventory for low water crossings?

Question 3: If yes, please provide information from the inventory. (Please include link to the inventory or provide adequate contact to request needed information if not directly accessible. You can also upload attachments, if needed.)

Question 4: Has your Area Office developed low water crossing design and countermeasure implementation protocols (i.e., barricades, flood sensors, passive signs, and active warning devices)?

Question 5: If yes, please provide information regarding the protocols. (Please include link to protocols or provide adequate contact to request needed information if not directly accessible. You can also upload the protocols as an attachment, if preferred.)

Question 6: With respect to low water crossings, has your Area Office developed any criteria/ methods for diagnosing problems and developing alternatives?

Question 7: If yes, please provide information regarding developed criteria /methods. (Please include link to the developed criteria or provide adequate contact to request needed information if not directly accessible. You can also upload files of the developed criteria as an attachment, if preferred.)

Question 8: Please list the different low water crossing countermeasures your Area Office has implemented (i.e., barricades, flood sensors, passive signs, active warning devices). For each of the listed countermeasures, please provide as much feedback as possible with respect to their functionality, installation, maintenance, operation, etc. You can also upload files of the developed criteria as an attachment, if preferred.

Question 9: Based on your experience, how would you categorize the success (or failure) of both passive and active devices utilized by your Area Office to improve visibility and alert motorists of flooding events at low water crossings?

Question 10: When selecting different low water crossing countermeasures for implementation, does your Area Office give consideration to location/scenario characteristics? (For example, you implement countermeasure Type A for scenarios that are Type 1 and Type 2.) If so, would you be able to share the main reasoning for your choices?

Question 11: How does your Area Office prioritize characteristics of locations where future device deployment is most needed?

Question 12: Are there any other relevant issues or ideas with respect to low water crossings which you would like to share/discuss (i.e., design considerations, operational challenges, need for connected vehicle technologies, and smartphone apps for flood hazard warning)? These can be issues you are already facing or could be suggestions that you identify as possible solutions for low water crossing locations.

Question 13: Are there any other comments you would like to share with the Project Team that were not specifically addressed through the previous questions? If so, please feel free to include your comment(s) in the comment box below.

APPENDIX B. LISTS OF FLOOD SENSORS

Table B.1. Pressure Sensors.

Manufacturer	Model	Figure	Operating Temperature	Resolution	Accuracy	Power Supply	Output	Listed Price
GE Druck	PDCR 1800 Transducer		-20 to 60°C (-4 to 140°F)	N/A	±0.10% FS BSL, Standard	10V	25–100mV	Starting at $954
	PTX 1800 Transmitter					9–30V	4–20mA	
Onset	HOBO® U20L Series Water Level Loggers		0° to 40°C (32° to 104°F)	<0.014kPa (0.002psi) 0.14cm (0.005ft)	± 0.1% FS	2/3 AA 3.6V Lithium	N/A	Logger $299 Base $124 Software $99
Global Water	WL400 Water Level Sensor		-40° to +85°C (-40° to +185°F)	Infinitesimal	±0.1% FS	8–36Vdc	4-20mA or 0.5–2.5Vdc	$605 to $1220
Global Water	WL430 Sewage Lift Station Wastewater Level Sensor		-17° to 93°C (0° to 200°F)	Infinite	±0.1% FSO	8–38Vdc	4–20mA	$1297
Global Water	WL450 Stainless Steel Water Level Transmitters		-10° to 80°C (14° to 176°F)	N/A	±0.1% 16B Digital Error Correction	10–28Vdc	4–20mA 2-wire loop Powered	$755 to $2183

Table B.1. Pressure Sensors (Continued).

Manufacturer	Model	Figure	Operating Temperature	Resolution	Accuracy	Power Supply	Output	Listed Price
Seametrics	PS98i		-5˚ to 70˚C (23˚ to 158˚F)	N/A	±0.25%FSO Static	9–24Vdc	4–20mA	$640
Seametrics	PS9800		-5˚ to 70˚C (23˚ to 158˚F)	N/A	±0.1% FSO Static	9–24Vdc	4–20mA	$759
Seametrics	PT12		-15˚ to 55˚C (5˚ to 131˚F)	N/A	±0.05% FSO (Typical Static) ±0.1% FSO (Maximum, Static)	9–16Vdc	3–10mA	$806
Seametrics	PT2X		-15˚ to 55˚C (5˚ to 131˚F)	0.0034% FS (typical)	±0.05%FSO (Typical, Static) ±0.1%FSO (Maximum, Static)	2 AA lithium 12Vdc Nominal, 6–16Vdc	N/A	$879 USB communic ations kit, includes Aqua4Plus software $322
Seametrics	LevelSCOUT		-20° to 60°C	0.0034% FS (typical)	±0.10% FS 0° to 40° C	1/2 AA 3.6V lithium	N/A	$416 USB communic ations kit, includes Aqua4Plus software: $322

Table B.2. Float Sensors.

Manufacturer	Model	Figure	Operating Temperature	Resolution	Accuracy	Power Supply	Output	Listed Price
Celesco	PT510		-40° to 90°C (-40° to 200°F)	Essentially Infinite	± 0.28%–±0.15%	8–40Vdc	4–20mA (2-wire) & 0–20mA (3-wire)	N/A
Celesco	PT420		-17° to 90°C (0 to 200°F)	Essentially Infinite	± 0.28% to ±0.15%	8–40Vdc	4–20mA (2-wire) & 0–20mA (3-wire)	N/A
Celesco	PT1MA		-40° to 90°C (-40° to 200°F)	± 0.003% Full Stroke	±0.10% FS	9–22Vdc	N/A	N/A
Celesco	PT9232		-40 to 60°C	0.01 ft	±0.10% FSO	2.5–5Vdc	Ω	N/A
Intermountain Environmental, Inc.	FP10C-RS (Replaced by FP10RF)		-40° to 90°C (-40° to 200°F)	Essentially Infinite	± 0.15% to ±0.28%	8–40Vdc	4–20mA (2-wire) & 0–20mA (3-wire)	$480 to $622.9

Table B.3. Bubbler Sensors.

Manufacturer	Model	Figure	Range	Operating Temperature	Accuracy	Power Supply	Output	Listed Price
Xylem	AMAZON BUBBLER		0 to 50 Psi 0 to 115.34 ft	-40° to 60°C	±0.02% FSO	10–16.5Vdc	4 to 20 mA	$3,345
Digital Control Company	Bubbler level Monitor (BLM)		0 to 100 ft	-30° to 60°C (-22°F to 140°F)	±1% of FSO	10–15Vdc 2 A max	4–20mA Relay 15A at 125Vac	$1,610
Tesco Controls, Inc.	Reactive Air Level Monitor		0 to 35 ft	-18 to 93°C (0 to 200 °F)	±0.125 inch	120Vac or 12Vdc	Analog 4–20mA	$3500 to $6500

Table B.4. Ultrasonic Sensors.

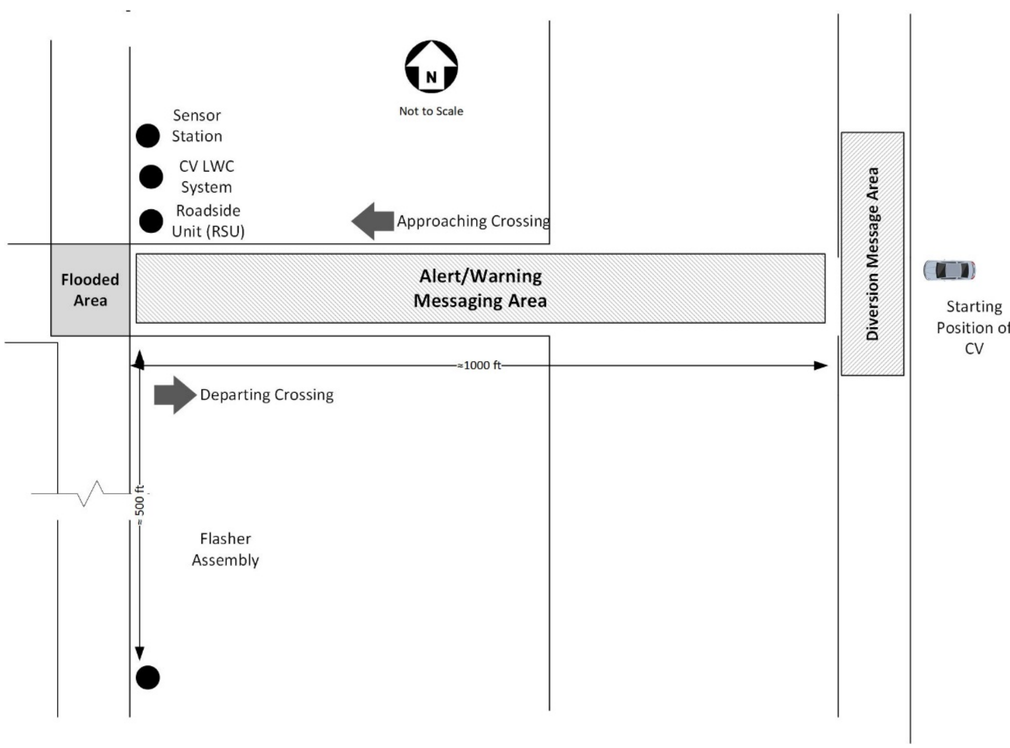
Manufacturer	Model	Figure	Range	Operating Temperature	Accuracy	Power Supply	Output	Listed Price
Campbell Scientific	SR 50 Series		1.6 to 32.8 ft	-45° to 50°C	±1 cm (0.4 in) or 0.4% of Distance to Target	9–18Vdc Powered by Data Logger 12Vdc (Power Supply)	N/A	$856.53 (Depends on Cable Length) $1249.15 (With Heater)
Senix	TOUGHSONIC Remote 50		1 to 50 ft	-40° to 70°C (-40° to 158°F)	Nominal 0.2% of range	10–30Vdc	N/A	Start at $849
ABB MEASUREMENT & ANALYTICS	LST400		0.5 to 15 m (1.6 to 50 ft)	-40° to 80°C (-40° to 176°F)	0.25% Full Span with Temperature Compensation or 3mm (0.11 in)	24Vdc or 110/220Vac	4–20mA	N/A
ABB MEASUREMENT & ANALYTICS	LST300		0.35 to 10 m (14 in to 32 ft)	-40° to 85°C (-40° to 185°F)	2mm (0.08in) or 0.20 % of Full Span	16–42Vdc	4–20mA	N/A
Endress+Hauser	Pro-sonic FDU91		up to 10 m (32ft)	-40° to 80°C (-40° to 176°F)	±2 mm	100–240Vac	4–20mA	$500 + (Transmitter) $1200

Table B.5. Radar Sensors.

Manufacturer	Model	Figure	Range	Operating Temperature	Accuracy	Power Supply	Output	Listed Price
Campbell Scientific	CS475A-L		0.5 to 35 m (1.6 to 114.8 ft)	-40° to 80°C	±2 mm (±0.0065 ft)	9.6–32Vdc	7mA	$2205.75
Flowline	EchoPro LR11		12 in to 32.8 ft (30 cm to 10 m)	-40º to 130ºC (-40º to 266ºF)	± 5mm	21.6–26.4Vdc	4–20mA	$1900
Endress+Hauser	Time-of-Flight Micropilot FMR20		up to 20 m (66 ft)	–40º to 80°C (–40º to 176°F)	up to ± 2 mm (0.08 in)	10.5–30Vdc	4-20mA	$750

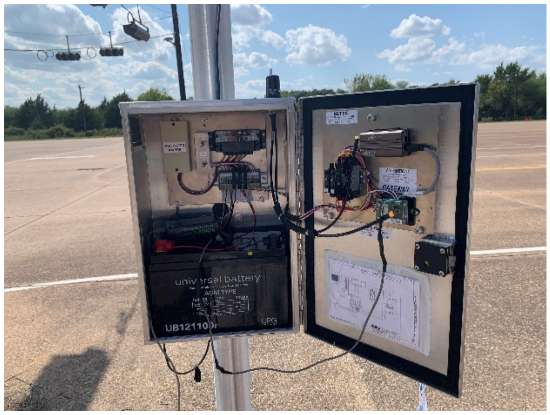
APPENDIX C. VERIFICATION TEST PLANS

Test Case No. and Title	**Test Case 1: CV Technologies Integrated at Low Water Crossing Operating in a Standalone Mode**
Test Objectives	The primary purpose of this test is to demonstrate the use of connected vehicle (CV) technologies directly integrated with a flood detection system to broadcast alerts and warning messages associated with a low water crossing or flood-prone section of a roadway.
Requirements Verified	The CV system, when connected directly to a flood detection system, can broadcast alerts and warnings to drivers about the status of a low water crossing or a flood-prone area on a roadway.
Brief Description	In this test, the CV system is triggered by flood sensors to activate two CV messages—a Level 1 alert that notifies drivers to watch for water on the roadway, and a Level 2 warning that notifies drivers that the crossing is closed due to flooding. Rising and dissipating water levels are simulated by placing (and removing) the flood sensors from buckets of water. The first sensor emulates water being detected on the roadway and activates the flashing assembly at the crossing. The message associated with a Level 1 alert is “Watch for Water on Roadway. Turn Around. Don’t Drown.” The message associated with a Level 2 alert is “Road Closed Due to Flooding. Turn Around. Don’t Drown.”
Test Setup and Configuration	<u>Field Installation</u> The figure below shows the configuration of the test area at the testbed.



Initial Configuration of Test Equipment

The research team has designated an area on the RELLIS test track to be the simulated flooded crossing. The team has installed a flood detection system adjacent to the designated area. The system uses the same technology as the standard Texas Department of Transportation (TxDOT) flood detection and warning system. It consists of a detection station installed on a pole and a flasher assembly that activates when the roadway floods.

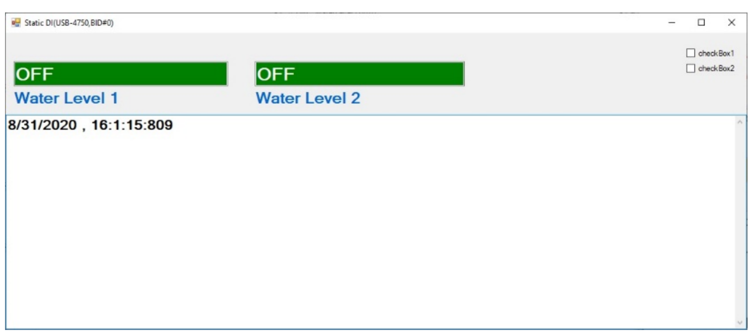


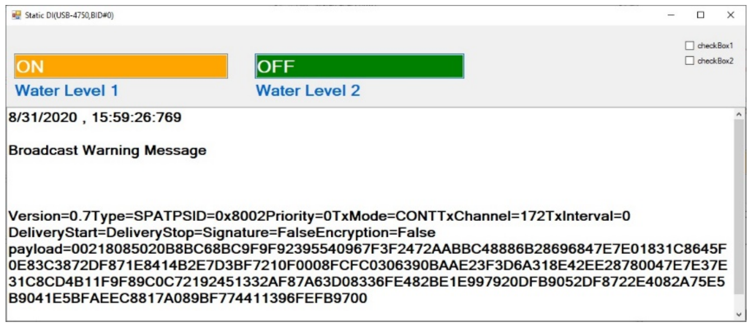
The research team has located the flasher assembly approximately 500 feet south of the test location. The flasher assembly is facing back toward the sensor station so the test administrator can see when the flasher assembly is activated.

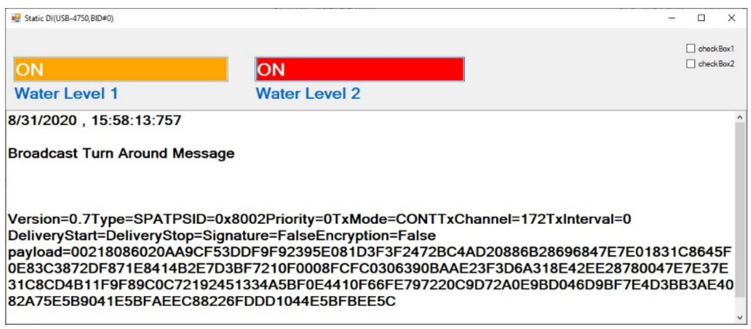
The research team will use two buckets of water of sufficient depth to activate the flood detection system. Each bucket of water represents a particular level of water over the roadway. The initial starting position of each sensor will be next to its designated bucket.

For this test, the low water crossing (LWC) CV application is connected directly to the sensor station. The research team has installed the LWC application on a laptop located next to the detection station. The LWC application monitors the status of the flood sensors and broadcasts preprogrammed messages via the roadside unit (RSU) when the sensors detect water. The research team has mounted the RSU on a pole adjacent to the test area.

Depending on the state of the roadway sensors, the LWC determines the type of message (no message, a Level 1 alert, or a Level 2 alert) to broadcast.







The research team has equipped a test vehicle with a portable CV test unit. The test unit contains an onboard unit (OBU) for receiving and decoding roadside safety messages broadcast from an RSU. A portable handheld unit located in the front seat with the driver displays the warning messages to the driver.

Test Procedure/ Script	<u>Test 1a: Flood sensors not active—CV *approaching* the crossing.</u> The initial position of the CV is outside the alert/warning message area of the designated flood area, heading westbound. When ready, the test administrator

will instruct the driver of the CV to drive through the designated flood area. The driver should indicate to the test operator what messages and alerts were received. The test administrator will record the response of the message displayed to the driver.

Test 1b: Flood sensors not active—CV *departing* the crossing.

The driver will position the CV west of the designated flood area, heading eastbound. Once ready, the test administrator will instruct the driver to drive through the designated flood area. The driver should report any messages displayed on the screen. The test administrator will record the response of the message displayed to the driver.

Test 1c: Level 1 flood sensors active—CV *approaching* the crossing.

The CV should return to the initial starting position from Test 1a. When ready, the test administrator will place Sensor 1 in a bucket of water to simulate the detection of water on the roadway. The flasher assembly will activate approximately 50 seconds after the test administrator has submerged the sensor. After the flasher assembly begins flashing, the test administrator will direct the driver of the CV to drive toward the designated flooded area for approximately 250 feet. The driver should indicate to the test administrator the content of any message received during the run. The test administrator will record the response of the message displayed to the driver.

Test 1d: Level 1 flood sensors active—CV *departing* the crossing.

The driver will position the CV west of the designated flood area, facing eastbound. Once the car is in position, the test administrator will instruct the driver to drive through the designated flood area. The driver should report any messages displayed on the screen. The test administrator will record the response of the message displayed to the driver.

Test 1e: Level 2 flood sensors active—CV *approaching* the crossing.

The CV should return to its initial starting position. Sensor 1 will remain in its bucket. When ready, the test administrator will place Sensor 2 in the second bucket of water to simulate that the crossing is now closed due to flooding. After placing Sensor 2 in the test bucket, the test administrator will direct the driver of the CV to drive through the designated flood area. The driver should indicate to the test administrator the content of any message displayed during the test run. The test administrator will record the response of the message displayed to the driver.

Test 1f: Level 2 flood sensors active—CV *departing* crossing.

The driver will position the CV on the west side of the designated flood area, heading eastbound. Once the car is in position, the test administrator will instruct the driver to drive through the simulated low water crossing. The driver should report any message displayed on the screen during the run. The test administrator will record the response of the message displayed to the driver.

Test 1g: Level 1 alert switches to Level 2 as the CV *approaches* the designated flood area.

The CV will return to its initial starting position east of the designated flood area, heading westbound. The test administrator will remove Sensor 2 from the water and dry the contacts. When ready, the test administrator will instruct the

CV driver to move toward the designated flood area. When the vehicle is approximately halfway to the crossing, the test administrator will activate Sensor 2, causing the message in the CV to switch from a Level 1 alert to a Level 2 warning. The driver should indicate to the test administrator the content of any message displayed during the run. The test administrator will record the response of the message displayed to the driver.

Expected Results

Test 1a: The CV should **NOT** display any messages or alerts to the driver when the vehicle is *approaching* the simulated low water crossing.

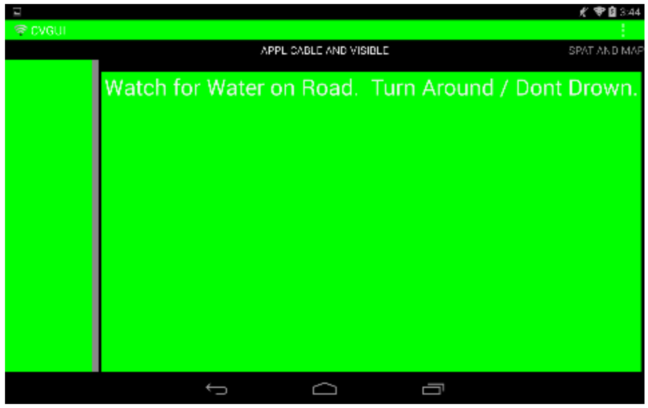
☒ Pass ☐ Fail

Test 1b: The CV should **NOT** display any messages or alerts to the driver when the vehicle is *departing* the simulated low water crossing.

☒ Pass ☐ Fail

Test 1c: The CV should display the Level 1 alert "**Watch for Water on Roadway. Turn Around. Don't Drown**" when the vehicle is *approaching* the simulated low water crossing.

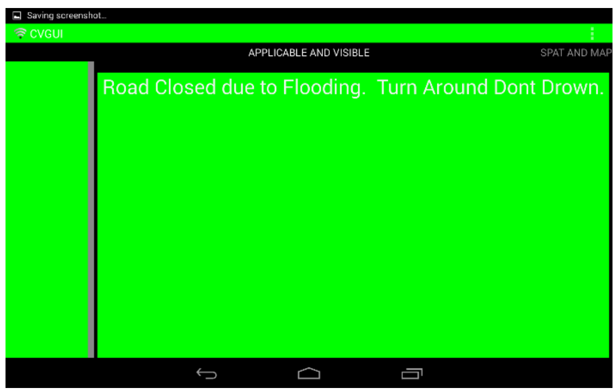
☒ Pass ☐ Fail



Test 1d: The CV should **NOT** display the Level 1 alert "Watch for Water on Roadway. Turn Around. Don't Drown" when the vehicle is *departing* the simulated low water crossing.

☒ Pass ☐ Fail

Test 1e: The CV should display the Level 2 warning message "**Roadway Closed Due to Flooding. Turn Around. Don't Drown**" when the vehicle is *approaching* the crossing.

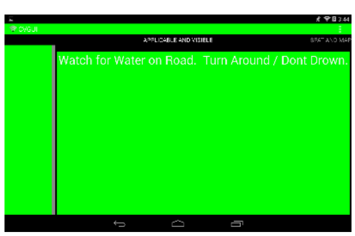


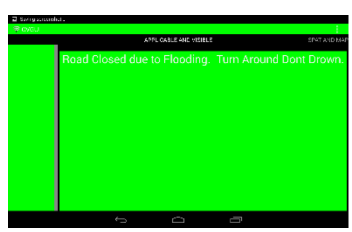
☒ Pass ☐ Fail

Test 1f: The CV should **NOT** display the Level 2 warning message "Roadway Closed Due to Flooding. Turn Around. Don't Drown" when the vehicle is *departing* the crossing.

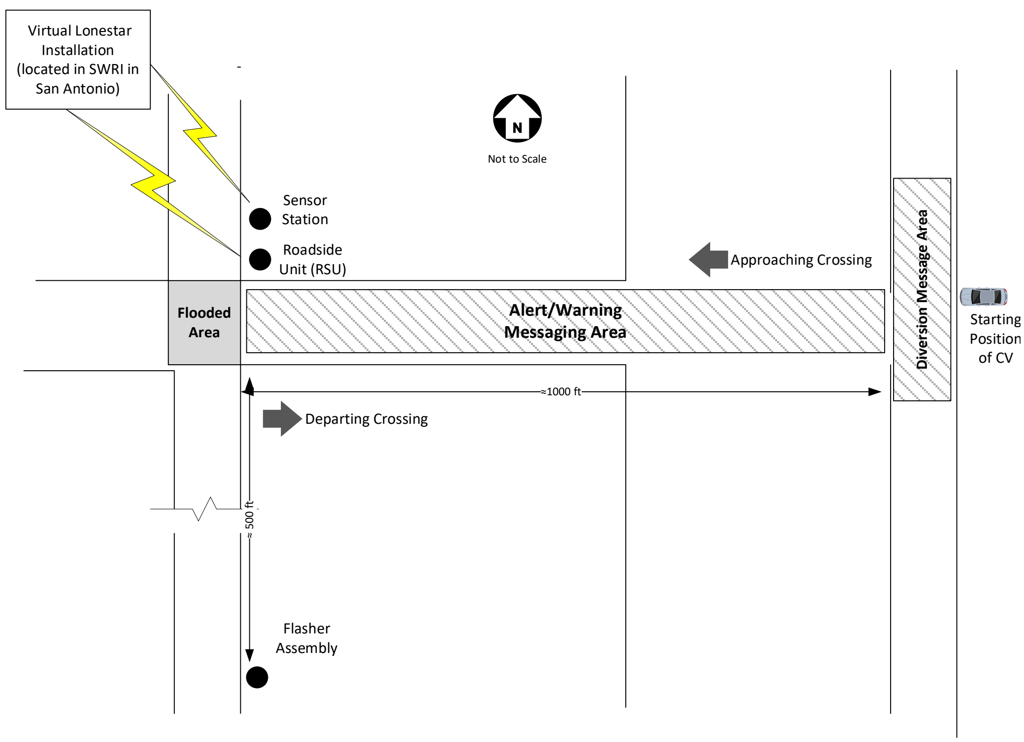
☒ Pass ☐ Fail

Test 1g: The CV switches from the Level 1 alert "**Watch for Water on Roadway. Turn Around. Don't Drown**" to a Level 2 alert as the vehicle approaches the designated flood area.





☒ Pass ☐ Fail

Test Case No. and Title	**Test Case 2: CV Technologies at Low Water Crossing Activated through TxDOT's LoneStar Traffic Management Software**
Test Objectives	The primary purpose of this test is to demonstrate the use of the TxDOT LoneStar Traffic Management System to generate CV alerts and warning messages associated with flooded low water crossings or sections of roadway.
Requirements Verified	The CV system can broadcast alerts and warnings to drivers about the status of a low water crossing or flood-prone areas on a roadway using the LoneStar Traffic Management System.
Brief Description	For this test, the research team has integrated the flood detection system with TxDOT's LoneStar Traffic Management System. The LoneStar system monitors the status of the flood sensors and activates the broadcast of the CV messages (Level 1 and Level 2 alerts) to the RSU via a cellular modem. The content of the message depends on the water levels measured by the sensors.
Test Setup and Configuration	<u>Field Installation</u> The figure below shows the configuration of the testbed.  <u>Initial Configuration of Test Equipment</u> The equipment configuration is the same as Test Case 1 except that the TxDOT LoneStar Traffic Management System monitors the status of the flood sensors. LoneStar connects to the flood detection system via a cellular modem. A virtual test version of the LoneStar system is running in Southwest Research Institute offices in San Antonio. As the research team places the water detection sensors in the buckets of water, the virtual LoneStar system determines the appropriate message to broadcast to the CVs. The LoneStar CV module broadcasts the same alerts as in Test Case 1.

Test Procedure/ Script	<u>Test 2a: Flood sensors not active—CV *approaching* the crossing.</u> The initial position of the CV is east of the defined flood area, heading in the westbound direction. When ready, the test administrator will instruct the driver of the CV to drive through the designated flood area. The driver should indicate to the test operator what messages and alerts were received. The test administrator will record the response of the message displayed to the driver. <u>Test 2b: Flood sensors not active—CV *departing* the crossing.</u> The driver will position the vehicle approximately 250 feet west of the designated flood area, heading eastbound. Once ready, the test administrator will instruct the driver to drive through the designated flood area. The driver should report any messages displayed on the screen. The test administrator will record the response of the message displayed to the driver. <u>Test 2c: Level 1 flood sensors active—CV *approaching* the crossing.</u> The CV should return to the initial starting position from Test 2a. When ready, the test administrator will place Sensor 1 in a bucket of water to simulate the detection of water on the roadway. The flasher assembly will activate approximately 50 seconds after the test administrator has submerged the sensor. After the flasher assembly begins flashing, the test administrator will direct the driver of the CV to drive toward the designated flood area for approximately 250 feet. The driver should indicate to the test administrator the content of any message received during the run. The test administrator will record the response of the message displayed to the driver. <u>Test 2d: Level 1 flood sensors active—CV *departing* the crossing.</u> Once on the west side of the designated area, the driver will position the vehicle facing eastbound. Once the car is in position, the test administrator will instruct the driver to drive through the designated flood area. The driver should report any messages displayed on the screen. The test administrator will record the response of the message displayed to the driver. <u>Test 2e: Level 2 flood sensors active—CV *approaching* the crossing.</u> The CV should return to its initial starting position. Sensor 1 will remain in its bucket. When ready, the test administrator will place Sensor 2 in the second bucket of water to simulate that the crossing is now closed due to flooding. After placing Sensor 2 in the test bucket, the test administrator will direct the driver of the CV to drive through the designated flood area. The driver should indicate to the test administrator the content of any message received during the test run. The test administrator will record the response of the message displayed to the driver. <u>Test 2f: Level 2 flood sensors active—CV *departing* crossing.</u> Once on the west side of the simulated crossing area, the driver will position the vehicle approximately 250 feet upstream of the crossing area, heading eastbound. Once the car is in position, the test administrator will instruct the driver to drive through the simulated low water crossing. The driver should report any message displayed on the screen during the run. The test administrator will record the response of the message displayed to the driver.

Test 2g: Level 2 flood sensors deactivated (Level 1 still activated)—CV *approaching* the crossing.

The CV will return to its initial starting position approximately 300 feet east of the designated flood area, heading westbound. Once the car is in place, the test administrator will direct the driver of the CV to drive through the designated flood area. When the vehicle is approximately halfway to the designated flood zone, the test administrator will remove Sensor 2 from the water and dry the contacts. This action should deactivate the Level 2 warning. The driver should indicate to the test administrator the content of any message displayed during the run. The test administrator will record the response of the message displayed to the driver.

Expected Results

Test 2a: The CV should **NOT** display any messages or alerts to the driver when the vehicle is *approaching* the simulated low water crossing.

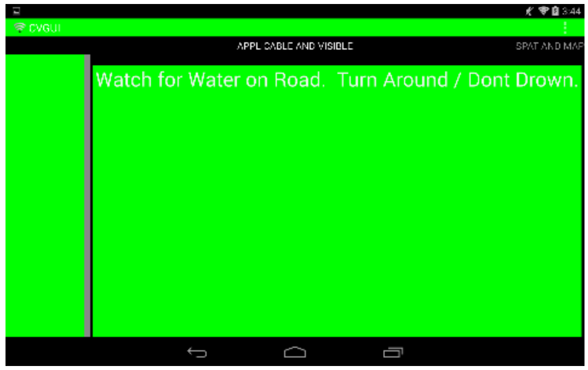
☒ Pass ☐ Fail

Test 2b: The CV should **NOT** display any messages or alerts to the driver when the vehicle is *departing* the simulated low water crossing.

☒ Pass ☐ Fail

Test 2c: The CV should display the Level 1 alert "**Watch for Water on Roadway. Turn Around. Don't Drown**" when the vehicle is *approaching* the simulated low water crossing.

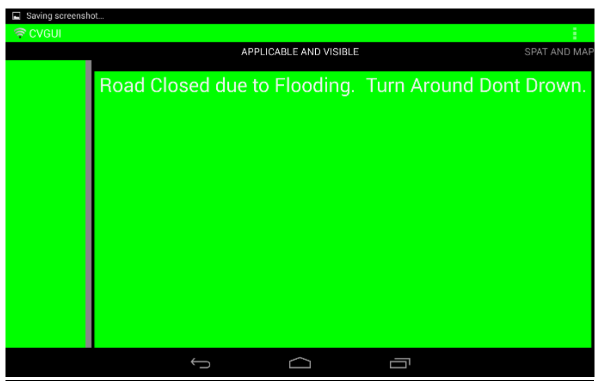
☒ Pass ☐ Fail



Test 2d: The CV should **NOT** display the Level 1 alert "Watch for Water on Roadway. Turn Around. Don't Drown" when the vehicle is *departing* the simulated low water crossing.

☒ Pass ☐ Fail

Test 2e: The CV should display the Level 2 warning message "**Roadway Closed Due to Flooding. Turn Around. Don't Drown**" when the vehicle is *approaching* the crossing.

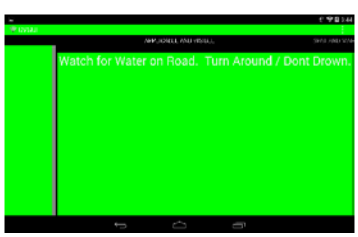


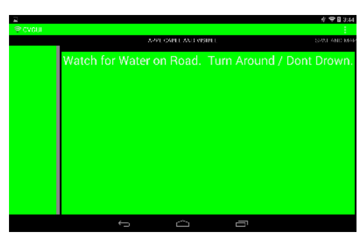
☒ Pass ☐ Fail

Test 2f: The CV should **NOT** display the Level 2 warning message "Roadway Closed Due to Flooding. Turn Around. Don't Drown" when the vehicle is *departing* the crossing.

☒ Pass ☐ Fail

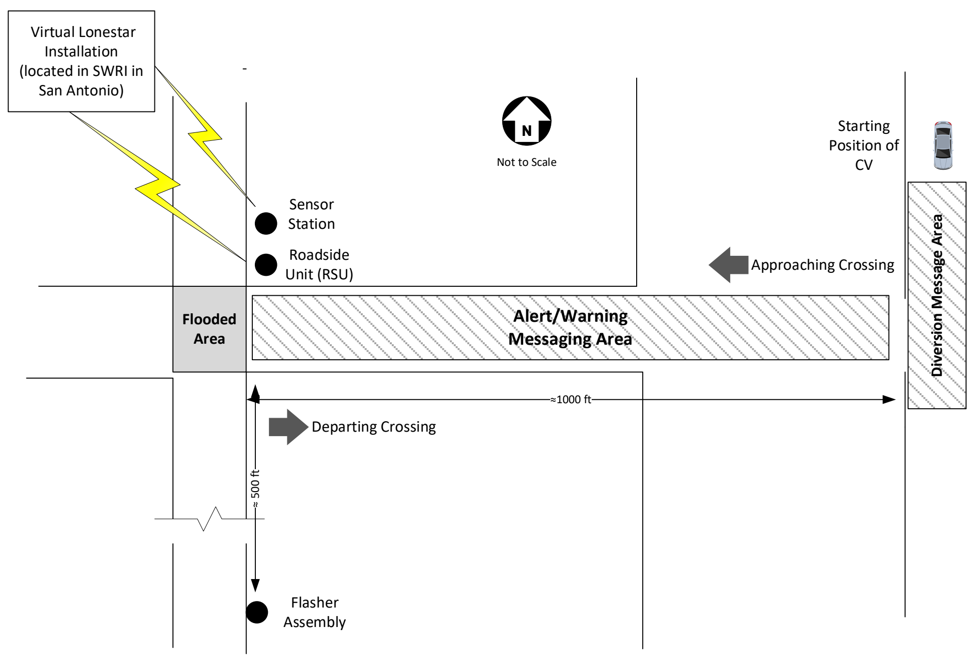
Test 2g: The CV display should switch from a Level 2 warning to the Level 1 alert "**Watch for Water on Roadway. Turn Around. Don't Drown**" when the vehicle is *approaching* the simulated low water crossing.





☒ Pass ☐ Fail

Test Case No. and Title	**Test Case 3: CV Technologies to Broadcast Diversion Messages Associated with a Low Water Crossing Activated**
Test Objectives	The primary purpose of this test is to demonstrate that the LoneStar Traffic Management System can broadcast diversion messages to motorists upstream of low water crossings or flood-prone sections of roadways via an RSU.
Requirements Verified	The CV system will be able to broadcast diversion messages upstream of a low water crossing or flood-prone area.
Brief Description	This test uses the same configuration as Test Case 2. For this test, the research team has established a diversion message zone on a roadway facility that parallels the crossing area. When the system detects flooding in the crossing, it generates a diversion message indicating that the crossing is closed due to flooding and that the vehicle should continue straight on its current path. This test uses the TxDOT LoneStar version of the application to monitor the status of the flood sensors and to generate the CV diversion message.
Test Setup and Configuration	<u>Field Installation</u>



Test Procedure/ Script	<u>Test 3a: Flood sensors not active—CV *approaching* diversion area.</u> The initial position of the CV is north of the defined diversion message area, heading southbound. The research team should NOT submerge either of the two flood detection sensors. When ready, the test administrator will instruct the driver of the CV to drive through the diversion message area. The driver should indicate to the test administrator the content of any messages and alerts displayed in the vehicle. The test administrator will record the response of the message displayed to the driver. After completing the test run, the CV should return to its original starting position.

Test 3b: Both sensors active (Level 1 and Level 2 alerts).

When ready, the test administrator will place both sensors in their designated buckets of water to simulate the blocking of the crossing by water. The flasher assembly should activate approximately 50 seconds after the test administrator places the sensors in the water. After the flasher assembly activates, the test administrator will direct the CV to drive through the diversion message zone. The driver should indicate to the test administrator the content of any message or alert displayed in the vehicle. The test administrator will record the response of the message displayed to the driver.

Test 3c: Switch from a diversion message to a Level 2 alert.

When ready, the test administrator will activate both sensors to simulate the blocking of the crossing by water. The initial position of the CV will be outside the diversion message zone. After the flasher assembly activates, the test administrator will direct the CV to drive through the diversion message zone and turn right toward the designated flood area. The driver should indicate to the test administrator the content of any message or alert displayed in the vehicle while the vehicle is in the diversion zone and after the turn is made. The test administrator will record the response of the message displayed to the driver.

Expected Results	Test 3a: The CV should **NOT** display any messages or alerts to the driver when the vehicle drives through the diversion message zone.	☒ Pass	☐ Fail
	Test 3b: The CV should display a diversion message to the driver indicating that the crossing is closed due to flooding, and the driver should continue in the original direction of travel parallel to the crossing.	☒ Pass	☐ Fail
	Test 3c: The CV should initially display a diversion message to the driver indicating that the crossing is closed due to flooding. After the vehicle turns, the CV message should change to a Level 2 alert.	☒ Pass	☐ Fail