UNIVERSITY OF TEXAS ARLINGTON

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Synthesis of Safety Applications in Winter Weather Operations

Mohsen Shahandashti, Ph.D., P.E.
Stephen Mattingly, Ph.D.
Seokyon Hwang, Ph.D.
Wasiq Ameen
Ferika Farooghi

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16. Abstract

Despite every precaution taken by the TxDOT maintenance operators, winter operations vehicles have been hit in the rear, causing injury to the operators as well as the travelling public. The objectives of this synthesis research project were to synthesize and critically evaluate existing methods and devices used by various TxDOT districts for enhancing the safety of winter weather operations and recommend appropriate practices for TxDOT maintenance crews for utilizing the best methods and devices during winter weather operations. The research findings were obtained through an extensive literature review, fact-finding surveys, structured follow-up interviews, and case studies. A thorough review of the literature was conducted to obtain a detailed understanding of methods used to increase the visibility of winter operations vehicles in Texas and in states other than Texas. The findings of the literature review were used to develop surveys. Responses were collected from 15 TxDOT districts and 10 states other than Texas. Based on the survey responses, structured follow-up interviews were performed with the individuals with the most experience in successful winter weather operations. Overall, the research team conducted six detailed follow-up interviews. The interview participants were asked to provide detailed information on safety methods for winter operations that has been presented as case studies. To ensure the most effective methods for winter operations in Texas, the researchers recommended consistent appearances for winter operations vehicles (for lighting, message signs, markings, etc.). They also recommended a winter Operations Management System be implemented to obtain the current conditions of roads and maintenance crews.

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Prepared for:
Texas Department of Transportation (TxDOT)

Project Manager
Joanne Steele, PMP, CSM

Prepared by:
Mohsen Shahandashti, Ph.D., P.E.
Stephen Mattingly, Ph.D.
Seokyon Hwang, Ph.D.
Wasiq Ameen
Ferika Farooghi

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UNIVERSITY OF TEXAS ARLINGTON | Department of Civil Engineering

425 Nedderman Dr., 416 Yates St.

Box 19308, Arlington, TX 76019

DISCLAIMER

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EXECUTIVE SUMMARY

Despite all precautions taken by the operators of maintenance vehicles, insufficient visibility and lack of proper support systems of winter operations vehicles cause many collisions. Critical analysis of successful methods and technologies was needed to recommend the best practices that will improve the safety of TxDOT winter operations, as well as save cost and time. The objectives of this research project were to (1) synthesize and critically evaluate existing methods and devices used by various TxDOT districts for enhancing the safety of winter weather operations; (2) identify and evaluate the applicability of innovative methods and devices used by other U.S. States; and (3) recommend appropriate practices for TxDOT maintenance crews.

The research findings were obtained through an extensive literature review, fact-finding surveys, structured follow-up interviews, and case studies. A thorough review of the literature was conducted to obtain a detailed understanding of methods used to increase the visibility of winter operations vehicles in Texas and in states other than Texas. The findings of the literature review were used to develop two questionnaires, one for all TxDOT districts and another for all states other than Texas to capture the current state of safety practices in winter weather operations. Responses were collected from 15 TxDOT districts and 10 states other than Texas. The responses from Texas were from the districts of Abilene, Amarillo, Atlanta, Austin, Bryan, Dallas, Lubbock, Lufkin, Odessa, Paris, Pharr, San Antonio, Tyler, Waco and Wichita Falls. Respondents outside Texas were from the states of California, Indiana, Iowa, Kansas, Massachusetts, Missouri, New York, North Dakota, Oregon and Utah. Based on the survey responses, structured follow-up interviews were performed with the individuals with the most experience in successful winter weather operations. In total, the research team conducted six detailed follow-up interviews. The interview participants were asked to provide detailed information on safety methods for winter operations that could be used as case studies.

The information collected from literature, survey questionnaire, interviews, and case studies were analyzed to present recommendations for safer winter weather operations in Texas. The researchers recommend that:

- Winter operations vehicles have a consistent appearance (for lighting, message signs, markings, etc.) in all TxDOT districts to make the vehicles more visible and recognizable to the general public.
- Warning lights be “amber and blue colored” LED lights, which could be dimmed and turned on/off by the operator. The pattern of lighting is recommended to be a “flashing pattern”. Additional heated lens could be used in districts that frequently experience heavy snowfall during winter.
- Message signs have “black text over orange background”. It is recommended that the signs say “Stay back 250 feet”. “Arrow boards” could be installed instead of message signs in case of inadequate space on vehicles.
- Retroreflective markings be in colors of red and white. It is recommended that the markings be in chevron stripe pattern and be installed on the back of the winter operations vehicles.
- A Winter Operations Management System (WOMS) be implemented to obtain the current conditions of roads and maintenance crews.
- Each TxDOT district have a dry shed (permanent or temporary) to ensure efficient loading of salt and/or brine on to winter operations vehicles.
- Each TxDOT district office in urban areas have an arrangement for maintenance personnel to be able to shower and rest during the most adverse winter weather conditions.

The recommendations clearly show that there are practices that could reduce the chances of collision of winter operations vehicles and improve the safety and efficiency of winter operations. The benefits of safe and efficient winter operations go beyond reduced operation costs by enhancing safety, satisfaction of the general public, infrastructure conditions and service life and transportation system reliability. Moreover, the results of this study could reduce administrative costs, and traffic congestion.

CHAPTER 1
INTRODUCTION

1-1 PROBLEM STATEMENT

Winter operations vehicle crashes cause significant economic and casualty losses in the U.S. (FHWA, 2018; Myers, 2017). According to the Federal Highway Administration (FHWA, 2018), approximately 117,000 people are injured, and 1,300 are killed in vehicle crashes on snowy, slushy and icy roads annually. According to the Iowa Department of Transportation (DOT), an average of 46 crashes each winter involve a winter operations vehicle; Iowa DOT has paid more than $1.2 million to repair vehicles and settle claims for injuries caused by winter operations vehicle crashes between 2009 and 2014 (USA Today, 2015). Despite recent developments in winter operations vehicle devices and methods, the insufficient visibility of the vehicles still cause many crashes (Muthumani et al., 2015). According to the National Climatic Data Center (NCDC) database, the number of heavy snow events was more than 25% of all winter weather events over the past decade in Texas. Thus, winter operations require more consideration than before in Texas (Perkins et al., 2011).

Despite all precautions taken by the operators of maintenance vehicles, accidents happen during winter weather operations. Low visibility during winter weather conditions is one of the main causes of winter operations vehicle crashes (Appendix A). Therefore, a comprehensive analysis of various devices for enhancing visibility of winter operations vehicle is necessary to identify the most appropriate devices and methods, which meet all regulations and internal policies of TxDOT. This consideration is important for TxDOT since it determines the best practices for making the winter operations vehicles visible to the traveling public in order to improve the safety of roads, maintenance crew, and the traveling public.

1-2 RESEARCH OBJECTIVES

The objectives of this research project were to (1) synthesize and critically evaluate existing methods and devices used by various TxDOT districts for enhancing the safety of winter weather operations; (2) identifying and evaluating the applicability of innovative methods and devices used by other U.S. States; and (3) recommend appropriate practices for TxDOT maintenance crews for utilizing the best methods and devices during winter weather operations considering the conditions of different TxDOT districts. These methods were evaluated and compared based on several factors including but not limited to enhanced visibility during winter weather operations (not getting covered by snow during operation and getting the best attention of the driving public), ease of implementation by TxDOT maintenance workforces, compatibility with existing TxDOT safety regulations and policies, potential for future upgrades, and compatibility with existing TxDOT maintenance management systems.

1-3 RESEARCH APPROACH

The information presented in this report was obtained through an extensive literature review, fact-finding surveys, structured follow-up interviews, and case studies. A thorough review of the literature was conducted to obtain a detailed understanding of methods used to increase the visibility of winter operations vehicles in Texas and in states other than Texas. The results of literature analysis are presented in Chapter 2. The findings of the literature review were used to develop two surveys, one for all TxDOT districts and another for all states other than Texas to capture the current state of safety practices in winter weather operations. The survey was conducted using an online survey platform (Qualtrics.com). Details about the survey has been presented in Appendices B, C, D and E. Survey responses were collected from 15 TxDOT districts and 10 states other than Texas. The information obtained from survey analysis has been presented in Chapter 3. Based on the survey responses, structured follow-up interviews were performed with individuals with the most experience in successful winter weather operations, in order to identify their best practices and lessons learned from real projects. The interview participants were asked to provide detailed information on safety methods for winter operations, which has been presented as case studies in Chapter 4. The information collected from literature review, survey questionnaires, interviews, and case studies were analyzed to present recommendations for the most effective methods for winter operations in Texas. These recommendations have been provided in Chapter 5.

CHAPTER 2
LITERATURE REVIEW ON SAFETY APPLICATIONS IN WINTER WEATHER OPERATIONS

2-1 INTRODUCTION

Winter operations vehicles operate under the most adverse winter conditions, generally moving at slower speeds than other traffic. The combined effect of low speed and low visibility in snowy weather cause a majority of the winter operations vehicle crashes (Myers, 2017). Seventy percent of all such crashes involve a collision into the rear of winter operations vehicles (Bullough et al., 2001). It is crucial for the state departments of transportation (DOT) in the United States to achieve a high level of visibility for winter operations vehicles during winter (Muthumani et al., 2015). Implementing the latest state-of-the-art technologies and devices can save additional cost and increase the efficiency of winter operations vehicles. The following chapter reviews different methods and devices that can be used to make winter operations vehicles more visible to the traveling public. At the end of this chapter, a summary of the methods and devices has been provided.

2-2 WARNING LIGHTS

Warning lights installed on winter operations vehicles play a significant role to increase the conspicuity of the vehicles for other drivers. The lights also increase surrounding visibility for the drivers operating the vehicles. The increased visibility of the winter operations vehicles due to the warning lights enhances the safety of the winter operations. Type of warning light bulb, color, intensity, pattern, location, and size represent the most critical factors affecting the conspicuity of warning lights.

2-2-1 Types of Warning Light Bulbs

Different types of warning light bulbs, such as light-emitting diodes (LEDs), high intensity discharge (HID), incandescent lights, and halogen lights, are available in the market. In the last two decades, LEDs and HIDs have increasingly been used as warning lights in vehicles (Muthumani et al., 2015). This section provides a brief discussion of the most important characteristics of these two common types of warning light bulbs.

2-2-1-1 LIGHT EMITTING DIODE (LEDS)

LED lights improve the visibility of winter operations vehicles by indicating the position and direction of travel (Muthumani et al., 2015). Longer service life, increased reliability, compact design, high efficiency, and low heat production represent the most important advantages of LED lights over other types of warning lights such as halogen lights, and incandescent lights (Eichhorn, 2006). Agencies have pervasively adopted LEDs as forward, rear, and side warning light systems due to their advantages compared to halogen, HID, and incandescent lights (Muthumani et al., 2015). In practice, LEDs could produce the threshold quantity of light energy more quickly than the other types of lights; this enhances the efficiency of LED lights (Eichhorn, 2006). In addition, LEDs have significant mechanical stress resistance, which increases the service life of LED lights (Eichhorn, 2006). The angular intensity variation of LEDs causes reduced visibility at off angles, but this can be solved by using a larger number of LEDs installed at different angles (Vogt and Miller, 2008).

2-2-1-2 HIGH INTENSITY DISCHARGE (HID)

In the last two decades, many agencies have adopted the HID as another type of warning light (Muthumani et al., 2015). For creating light, HID lamps require a considerable amount of power, but then less power to preserve the created light (Muthumani et al., 2015). Overall, HIDs consume more power when compared to LEDs (Muthumani et al., 2015). Based on a study conducted by Vogt and Miller (2008) for the Minnesota Department of Transportation (MnDOT), the average power used by all LED fixtures remains significantly lower than HID. Cheng and Cheng (2006) showed that LEDs could save up to 60% power compared with HIDs. Moreover, LED lights are brighter than HIDs (McCullouch and Stevens, 2008). However, as it is shown in Figure 2-1, more snow could accumulate on their surface compared to HIDs (Vogt and Miller, 2008).

Figure 2-1 Comparison between HID (left) and LED (right) Lights after Heavy Snow Conditions (Vogt and Miller, 2008).

2-2-2 Color of Warning Lights

2-2-2-1 Different Light Colors and Motorist Perception

The color of a light plays a significant role in the ability of a driver to notice a winter operations vehicle (Henderson, 2018). Several state DOTs and related agencies investigated the characteristics of warning light colors (e.g. blue, amber, red, white, and green) and their impact on highway worker safety (Howell et al., 2015). Each state has its own preferred LED color, which may be different from the others. Table 2-1 illustrates colors of lights recommended by studies in some DOTs. Ullman et al. (1998b) carried out a research study on behalf of TxDOT to investigate human factors and driver behavior. Surveys were conducted in Dallas-Fort Worth, Houston and San Antonio to assess motorists' interpretations of special vehicle warning light colors. The goal was to come up with a warning light standard by conducting a survey of warning light policies. The survey showed that highway vehicle fleets traditionally use amber as the primary light. Using only an amber light may not reflect the true severity level of hazardous situations (Ullman et al. 1998b). Ullman et al. (1998b) studied the effect of two different light systems on the speed of motorists, in Texas. They compared the use of yellow light with the combination of yellow and blue lights, at five locations. The results showed that combining blue light with yellow light reduced the speed of motorist by 5 to 6 miles per hour, at two locations. Its application remains limited for DOT vehicles because its overuse may blunt its impact in the conspicuity of law enforcement and emergency vehicles (MnDOT, 2013). Figure 2-2 illustrates the Iowa Department of Transportation's installation of flashing white and blue lights on the back of 220 snowplows in order to improve safety, which resulted in about a 200% decrease in the number of snowplow involved collisions (Henderson, 2018).

Table 2-1 Light colors recommended by studies in some DOTs

State DOT	Preferred color(s)	References
Indiana DOT	Amber	McCullouch and Stevens (2008)
Iowa DOT	Amber + Additional color	Kamyab et al. (2002)
Minnesota DOT	Amber + Blue	Vogt and Miller (2008)
Ohio DOT	Amber + Green + White	ODOT (2012)

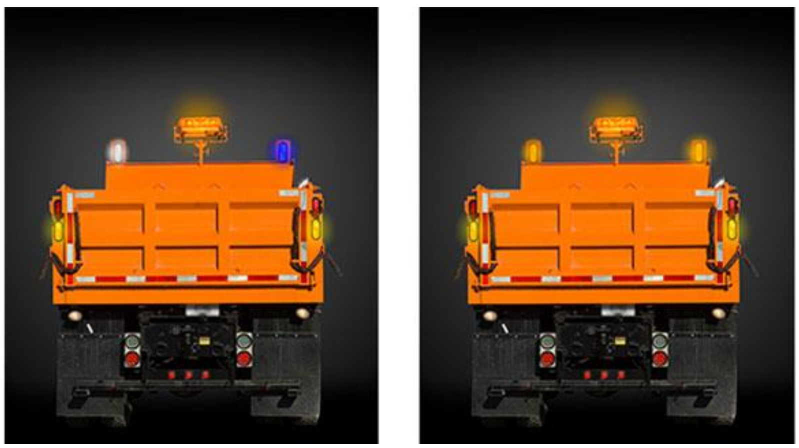


Figure 2-2 Color combination on snowplows to enhance safety: Left picture shows the latest blue lights on some snowplows and picture to the right shows enhanced amber lights on some DOT snowplows (Henderson, 2018).

Ullman et al. (1998a) stated that color plays an essential role in motorist perception, memory coding, and the pattern recognition process. Ullman et al. (1998b) indicated that drivers commonly associate the amber warning light with highway construction and maintenance vehicles and red warning lights with emergency responder vehicles. Motorist perceptions associate amber-only lights with less hazardous situations compared with other colors like blue or red (Ullman et al., 1998b).

2-2-2-2 Different Light Colors and Weather Conditions

Multiple studies investigate the relation between color and conspicuity and show that some colors are more visible and distinct than others in different weather conditions (Owusu-Ansah, 2010). A blue light alone has low visibility in dense fog; therefore, it must be combined with red or other similar lights, which remain highly visible in dark and dense fog conditions (Otas et al., 2012). Among different shades of LED light colors, reddish yellow represents the best color to use in foggy weather (Kurniawan et al., 2007). In general, a yellow light has better fog penetration capabilities than white lights (Muthumani et al., 2015; Jin et al., 2015). As Figure 2-3 illustrates, due to the dependence of light scattering on wavelength, the correlated color temperature of white LEDs increases with the increase of the fog density (Otas et al., 2012).

a) b) c)

Figure 2-3 Image of the object in the fog chamber under illumination by the white LED with additional white light falling from top for different densities of fog (a) low, (b) average, and (c) high density respectively (Otas et al., 2012).

2-2-3 Intensity

Muthumani et al. (2015) suggested that LED lights could be bright enough to warn those following behind winter operations vehicles. Although many transportation agencies choose the brightest light bulb type possible for warning lights, the warning lights should not be too bright because the intensity of the LED lights may distract or blind other motorists (Muthumani et al., 2015). Table 2-2 summarizes AASHTO's recommendations for daytime and nighttime intensities, arranged by light source. The units are in candelas, a SI unit that is equivalent to lumens (Howell et al., 2015).

Table 2-2 Light Source Intensity Ranges (Howell et al., 2015)

Light Source	Intensity (by Form Factor Method)		
	Daytime	Nighttime	
	Minimum	Minimum	Maximum
Halogen	3500	900	2200
LED	4000	1650	*
Strobe	3500	1200	2200

*Note that a maximum value for the LED sources was not found

2-2-4 Pattern

To improve the visibility and conspicuity of the winter operations vehicles to nearby drivers, different flashing patterns can be used (Muthumani et al., 2015). Although flashing lights increase the conspicuity of a winter operations vehicle for nearby drivers, they can reduce the ability of the drivers to perceive the speed of an oncoming winter operations vehicle (Muthumani et al., 2015). According to a survey conducted for the MnDOT, the combination of flashing lights and steady burning lights can improve the visibility of the winter operations vehicles (Yonas & Zimmerman, 2006). In this combination, flashing lights should be less bright than steady burning lights (Yonas & Zimmerman, 2006).

2-2-5 Location

Forward warning lights are usually mounted above the cab and truck bed of winter operations vehicles. In some cases, these warning lights are not 100% visible from the rear, the location of them thus should be specified meticulously to make sure that they have 360 degrees of visibility (Muthumani et al., 2015). In order to reduce the snow formation and improve airflow around rear warning lights, the North Dakota Department of Transportation (NDDOT) recommends elevating rear-warning lights. For rear lights, flush mounted is commonly used in conjunction with pole or telespar mounted lights, single or multiple beacons, and surface mounted lights (Muthumani et al., 2015).

Based on the following drivers' line of sight, Muthumani et al. (2015) proposed a mounting location for steady burn and flashing lights. Drivers following winter operations vehicles with a longer viewing distance can see elevated warning lights easily, but at a shorter distance, drivers will have a limited view of the back of the winter operations vehicles as shown in Figure 2-4 (Muthumani et al., 2015). Therefore, the vehicles should be equipped with additional warning lights in the drivers' line of sight within the shorter viewing distance.

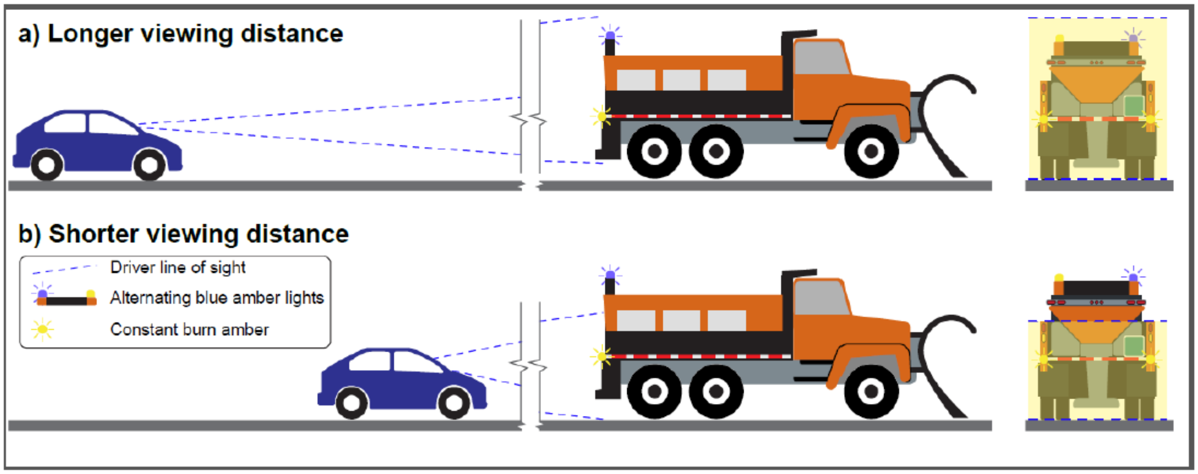


Figure 2-4 Proposed mounting locations for flashing and steady burning lights (Muthumani et al., 2015).

A survey of the New York State Department of Transportation (NYSDOT) showed during heavy snow blowing, operators prefer cab-mounted lights on the passenger side away from their line of sight rather than on the driver side (Eklund et al., 1997). Bullough et al. (2001) also suggested installing a passenger side auxiliary headlight and give operators an option to turn on the light in inclement weather conditions.

2-2-6 Size

The size of LED warning lights must also be considered. Although McCullouch and Stevens (2008) mentions that the visibility of larger lights remains higher than smaller ones, even though the smaller lights may be brighter than the larger ones. Bullough and Rea (1997) found that operators prefer narrow-beam light sources (spot lamp) compared to the wide-beam light sources (flood lamps) due to the reduction in the amount of back-scattered light.

2-3 HEATED LENS

A vehicle light includes several components such as light bulb (lamp), reflector, and lens. In case of the LED light bulb, since the bulb does not produce enough heat, ice accumulation may occur on the surface of the lens. Thus, LEDs may require a heated lens to stay clear during snowy operations. A heated lens consists of a conductive grid system that warms the lens surface and a sensor to measure ambient temperature. The heated lenses provide consistent melting of snow and ice. Therefore, the lights remain clear of snow and ice to keep the winter operations vehicles conspicuous during snowy weather operations. Muthumani et al. (2015) recommended a control switch that can turn on or off the heated lens based on different ambient temperature (Muthumani et al., 2015). Figure 2-5 illustrates components of a heated lens and the lens conductive grid system. Heated lenses require additional amperage to be helpful in severe winter weather conditions (Muthumani et al., 2015).

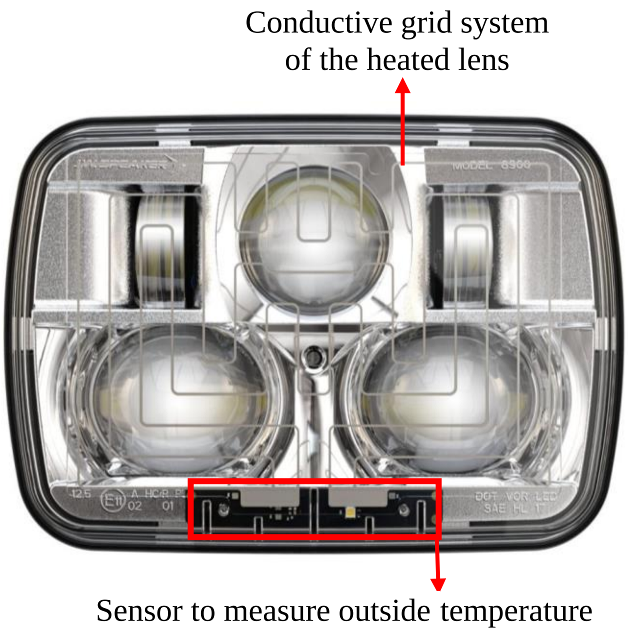


Figure 2-5 Heated lens components (4WP, 2018)

2-4 MESSAGE SIGNS

Message signs are illustrations on the back of winter operations vehicles that increase the visibility of the vehicles to any following drivers. This section presents the message signs used by the Ontario, California, Minnesota, Ohio, Pennsylvania, Michigan, New Jersey, Kentucky and Kansas departments of transportation (DOTs), and focuses on the coloring and patterns of the signs.

2-4-1 Ontario

In 2015, Ministry of Transportation of Ontario (MTO) published a study focusing on message signs (MTO, 2015). The study determined that message signs should be consistent in appearance so that they can be recognized easily. The study investigated the conspicuity (easily observable) of panels. MTO conducted tests with nine different color and sheeting combinations during daytime and night-time winter conditions. The tests demonstrated that the best conspicuity panel is a checkerboard pattern in fluorescent yellow-green and black. Based on the study, the MTO has developed standard messaging signs to alert other drivers of the dangers the winter operations vehicles may exert on the traffic. A standardized message sign is shown in Figure 2-6 (MTO, 2015).

Figure 2-6 Message sign on the back of winter operations vehicles (MTO, 2015)

2-4-2 California

Winter operations vehicles in California display message signs as black letterings over yellow backgrounds. The signs inform drivers to drive safely and to stay away from the winter operation vehicles (Caltrans, 2017). Figure 2-7 shows a message sign with yellow background used by Caltrans.

Figure 2-7 Message sign on the back of a winter weather operations vehicle in California (Caltrans, 2017)

2-4-3 Minnesota

The message signs on the winter operations vehicles of Minnesota instruct the drivers to stay back during the application of brine solution, traditional salt or sand as can be seen in Figure 2-8 (Star Tribune, 2017).

Figure 2-8 Message sign behind a winter operations vehicle in Minnesota (Star Tribune, 2017)

2-4-4 Ohio

The Ohio Department of Transportation (ODOT) ran a Winter Safety campaign to remind the traveling public to remain safe during winter driving conditions. These efforts have included placing "Ice & Snow…Take It Slow" decals on all of Ohio's snowplow trucks (ODOT, 2011). Figure 2-9 shows the safety campaign decals on the back of a snowplow.

Figure 2-9 "Ice & Snow…Take It Slow" decals on ODOT's snowplow trucks (ODOT, 2011)

2-4-5 Pennsylvania

Winter operations vehicles in Pennsylvania carry a message sign instructing drivers to stay 100 feet away from the vehicles, as shown in Figure 2-10 (WITF, 2019).

Figure 2-10 Message sign on the back of a winter operations vehicle in Pennsylvania (WITF, 2019)

2-4-6 Michigan

Winter operations vehicles in Saginaw County (Michigan) have yellow message signs accompanied with red and white striped warning signs on the back, as shown in Figure 2-11 (Saginaw News, 2012).

Figure 2-11 Winter operations vehicles in Saginaw County (Michigan) with message signs at the back (Saginaw News, 2012)

2-4-7 New Jersey

Winter operations vehicles in Sussex County (New Jersey) use orange message signs, warning other drivers to stay back during their winter operations (New Jersey Herald, 2012). An example is shown in Figure 2-12.

Figure 2-12 Message sign on the back of a winter operations vehicle of Sussex County, New Jersey (New Jersey Herald, 2012)

2-4-8 De-icing Message Signs

Anti-icing liquid can be sprayed on a highway before a storm to prevent snow and ice from forming and sticking to the highway. It can be placed along a section of highway or at specific locations prone to icing, such as bridge decks. Winter operations vehicles could use de-icing warning messages (MTO, 2018). An example is shown in Figure 2-13.

Figure 2-13 Anti-icing message sign on the back of a winter operations vehicle of MTO (MTO, 2018)

Winter operations vehicles of the Kentucky DOT (Lake News 2012) and the Kansas DOT (KDOT, 2017) use de-icing message signs on the back of their vehicles during operations (Figure 2-14).

Figure 2-14 Anti-icing operations message signs on the back of winter operations vehicles in Kentucky and Kansas (Lake News, 2012 (left); KDOT, 2017 (right))

The winter operations vehicles of British Columbia also puts anti-icing message signs (Figure 2-15) on their backs during winter weather operations (Province, 2014).

Figure 2-15 "Anti-icing" message sign on the back of a winter operation vehicle of British Columbia (Province, 2014)

2-4-9 Traveler Warning Signs

Traveler warning signs are message signs informing travelers to use precautions while driving down icy roads.

During inclement winter weather conditions, Michigan Department of Transportation (MDOT)'s Traffic Operations Center (TOC) / Traffic Message Channel (TMC) can become overwhelmed by public inquiries regarding road safety. To inform the general public more efficiently about the latest road safety conditions, the TOC utilizes warning signs to advise roadway users of necessary weather-related information. The signs increase real-time knowledge of prevailing conditions, and increase the safety of civilian motorists and DOT operations personnel (Cook, 2016). Examples of advisory and warning signs are provided in Figure 2-16.

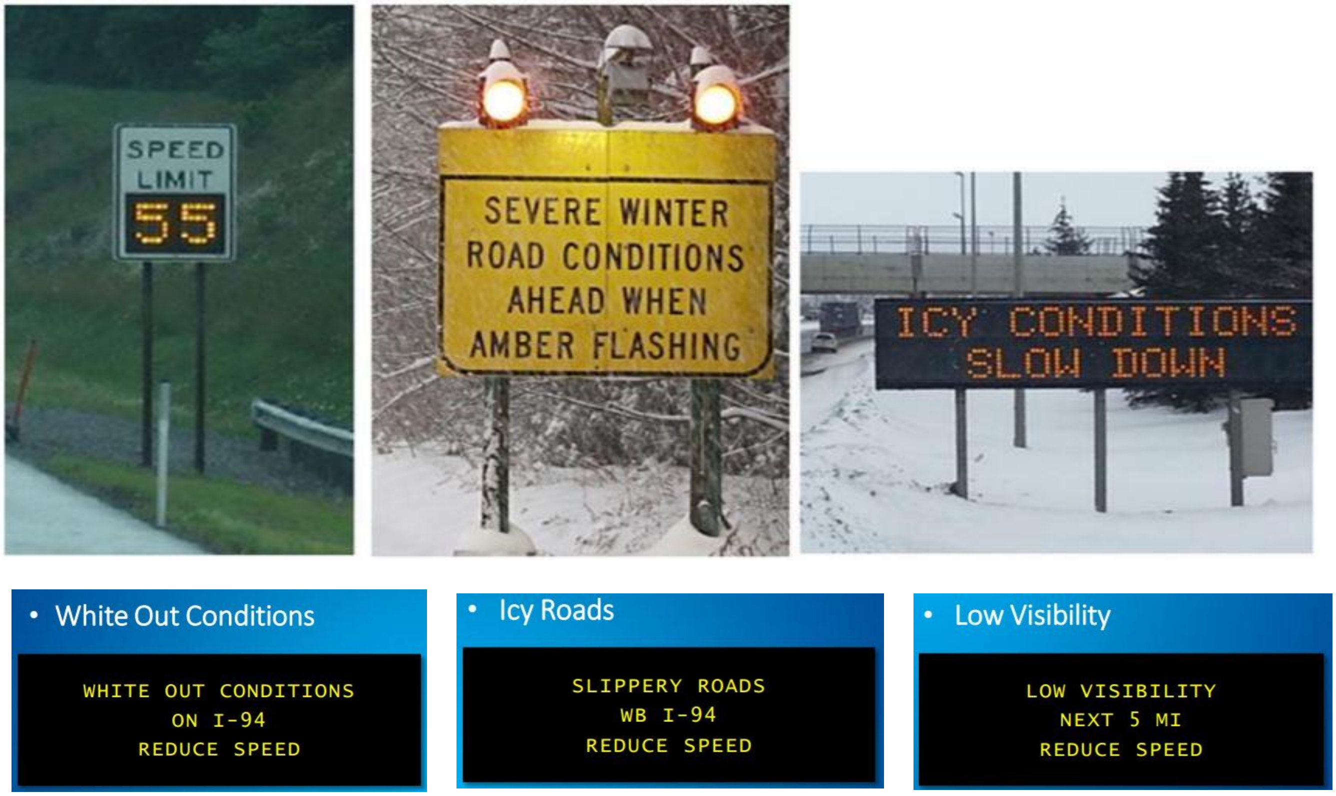


Figure 2-16 Examples of Motorist Advisory and Warnings signs in Michigan (Cook, 2016)

California uses tire chain control checkpoints to inform drivers that they need to install chains on their tires for better traction (Caltrans, 2018). Officials typically establish these checkpoints during a snowstorm and remove them after the storm ends (Figure 2-17).

Figure 2-17 Chain control checkpoint (Caltrans, 2018)

In Kansas, KDOT maintenance crews supply travel information to the public through traveler warning signs (KDOT, 2017). They input important travel updates, like the fixed message shown in Figure 2-18, on roadside message boards.

Figure 2-18 Fixed traveler message sign warning drivers of icy road conditions in Kansas (KDOT, 2017)

2-4-10 Summary

This section shows the importance of message signs for the visibility of winter operation vehicles. The DOTs of Ontario, California, Minnesota, Ohio, Pennsylvania, Michigan, New Jersey and Kansas has developed colorings and patterns for message signs on the back of their winter operation vehicles. Table 2-3 summarizes the message sign colors used in some DOTs.

Table 2-3 Message sign colors used in some DOTs

<table>
<tr><th colspan="2">State DOT</th><th>Color of text</th><th>Color of background</th></tr>
<tr><td colspan="2">Ministry of Transportation of Ontario (MTO)</td><td>Black</td><td>Yellow</td></tr>
<tr><td colspan="2">California DOT</td><td>Black</td><td>Yellow</td></tr>
<tr><td colspan="2">Michigan DOT</td><td>Black</td><td>Yellow</td></tr>
<tr><td colspan="2">Minnesota DOT</td><td>Black + Red</td><td>White</td></tr>
<tr><td colspan="2">Ohio DOT</td><td>Black</td><td>Orange</td></tr>
<tr><td colspan="2">New Jersey DOT</td><td>Black</td><td>Orange</td></tr>
<tr><td colspan="2">Pennsylvania DOT</td><td>Black</td><td>Orange</td></tr>
<tr><td rowspan="4">De-icing Message Signs</td><td>MTO</td><td>Black</td><td>Yellow</td></tr>
<tr><td>Kansas DOT</td><td>Black</td><td>Orange</td></tr>
<tr><td>Kentucky DOT</td><td>Black</td><td>Orange</td></tr>
<tr><td>British Columbia Ministry of Transportation</td><td>Black</td><td>White</td></tr>
</table>

2-5 RETROREFLECTIVE MARKINGS

Retroreflective markings reflect light back to its source with a minimum amount of light scattering. Retroreflective markings are usually added on the rear and side of winter operation vehicles, which increase the visibility of the vehicles at night and low visibility conditions.

2-5-1 Ontario

MTO uses retroreflective tape on the back of their winter operations vehicles. The brackets at the tailgate (hinged flap at the back of a winter operations vehicle) of the vehicles are bordered with red and white retroreflective tape, fully outlining the rear tailgate. Traffic coming from behind the vehicles get an increased perception about the dimensions of the vehicles due to the placement of the retroreflective tapes (Dow & Pearsall, 2014). An example of a winter operations vehicle bordered with red and white retroreflective tape at the tailgate is shown in Figure 2-19.

Figure 2-19 Red and white retroreflective tape fully outlining the rear tailgate of a winter operations vehicle in Ontario (Dow & Pearsall, 2014)

2-5-2 New Brunswick

SNC Lavalin O&M, a Canadian company responsible for the operations, maintenance, and rehabilitation of 275 kilometers (about 171 miles) of Trans-Canada Highway in New Brunswick, Canada, installs bright retroreflective orange tape on the wing plows of their winter operation vehicles (SNC Lavalin O&M, 2017). However, the retroreflective tape often becomes obscured by wet snow collecting on them or invisible due to whiteout conditions behind the wing plow. The installation of the tape did not reduce the number of collisions. SNC Lavalin O&M fabricated a new system called the "Safety Swing Arm" to reduce the number of accidents occurring in winter conditions. The Safety Swing Arm is a 2.7 meter (about 8 feet and 10 inches) mechanical arm with high intensity flashing lights and retroreflective panels, installed on the back of the winter operations vehicles (SNC Lavalin O&M, 2017). When the right side wing plow of the vehicle is deployed, the arm simultaneously extends to create a further visual and break-a-way physical barrier between the motorists and the right wing plow. After the introduction of the Safety Swing Arm in fall 2013, no collisions have been recorded between motorists and the winter operations vehicles' right wings (SNC Lavalin O&M, 2017). An illustration of the Safety Swing Arm with retroreflective panels is shown in Figure 2-20.

Figure 2-20 Safety Swing Arm with retroreflective markings (SNC Lavalin O&M, 2017)

2-5-3 Iowa

The Iowa Department of Transportation (Iowa DOT) does not allow the buildup of snow and slush on retroreflective signs. The signs must be cleaned and kept conspicuous. Any new retroreflective signs installed on their winter operations vehicles need to retain visibility for at least 10 years (CTRE, 2006). The signs are cleaned manually using a power/pressure washer after every maintenance operation (CTC & Associates LLC, 2016). A salt removing chemical (known as Salt-Away) and soap is used to remove as much snow and dirt possible from the surfaces of the winter operations vehicles (CTC & Associates LLC, 2016).

2-5-4 Alberta

In the province of Alberta, using two strips of retroreflective tape on the back of the winter operations vehicles illuminates the vehicles for drivers approaching from behind (Paulichuk, 2005). The most commonly used color combinations for reflective markings are red and white. However, retroreflective materials become useless if they get covered by snow. Therefore, the most significant concern is to keep the reflective markings 100% clean (Muthumani et al., 2015).

2-5-5 Virginia

The Virginia Department of Transportation (VDOT) marks their winter operation vehicle with red and white retro-reflective markings on the sides (Washington Top News, 2015). Illustration provided in Figure 2-21.

Figure 2-21 A winter operations vehicle of Virginia DOT with red and white retroreflective markings on the side (Washington Top News, 2015)

2-5-6 Ohio

The Ohio Department of Transportation (ODOT) uses a combination of yellow and green colors as warning signs. ODOT suggests that human eyes detect green easier than other colors. They will be the first state to use green warning colors (ODOT, 2018). The warning signs are shown in Figure 2-22.

Figure 2-22 Warning signs on the back of winter operations vehicles in Ohio (ODOT, 2018 (left); Barbaccia, 2014 (right))

2-5-7 Pennsylvania

The backs of winter operations vehicles in Pennsylvania have red and yellow warning signs (Daily American, 2017), illustrated in Figure 2-23.

Figure 2-23 Warning sign on the back of a new winter operations vehicle in Pennsylvania (Daily American, 2017)

2-5-8 Indiana

The winter operations vehicles in Indiana use red colored V-shaped warning signs on the back of the vehicles. The Indiana Department of Transportation (INDOT) V-Box spreaders (McCullouch and Stevens, 2008) use distinct warning signs (Figure 2-24). The V-Box spreader attaches to winter operation vehicles to place de-icing materials on road surfaces; the spreaders are either hydraulic or gasoline operated.

Figure 2-24 Warning sign on the back of Indiana DOT V-Box spreader (McCullouch and Stevens, 2008)

2-5-9 Connecticut

The Connecticut Department of Transportation marks the back of their winter operations vehicles in warning stripes of blue and white (CT Mirror, 2015). The illustration is provided in Figure 2-25.

Figure 2-25 Warning signs on the back of a winter operations vehicle in Connecticut (CT Mirror, 2015)

2-5-10 Summary

This section discusses the retroreflective markings used in the winter operations of Ontario, New Brunswick, Iowa, Alberta, Virginia, Ohio, Pennsylvania, Indiana and Connecticut. Retroreflective markings are easy to install on any surface of the winter operation vehicles. They do not require wiring or specially designed surfaces to function. However, snow and dirt deposits on the markings may obscure their visibility (NHTSA, 2001). For proper functionality of retroreflective markers, the markings must be kept clean and conspicuous. Table 2-4 summarizes the retroreflective marking colors used in some DOTs

Table 2-4 Retroreflective marking colors used in some DOTs

State DOT	Preferred colors
Ministry of Transportation of Ontario (MTO)	Red + White
New Brunswick Transportation & Infrastructure	Red + White
Ministry of Transportation of Alberta	Red + White
Virginia DOT	Red + White
Ohio DOT	Green + Yellow
Pennsylvania DOT	Red + Yellow
Indiana DOT	Red + Yellow
Connecticut DOT	Blue + White

2-6 REAR AIRFOIL

Rear airfoils or tailgate (rear) deflectors are metal flaps attached to the back of winter operations vehicles; the airfoils direct the air flow of a moving vehicle down the back to prevent snow build up on the rear lights and retroreflective markings. The diverted air flow from the top of the vehicle creates an aerodynamic shear caused by the high momentum air flow, which prevents the adhesion of snow on the rear surfaces. An airfoil test conducted by the Nevada DOT in 2008 (NDOT, 2008) is shown in Figure 2-26.

Figure 2-26 Airfoil test: Without airfoil and more snow accumulation on the rear (left) and with airfoil and less snow accumulation on the rear (right) (NDOT, 2008)

Investigations conducted to establish the effectiveness of airfoils (NDOT, 2008) found that airfoils provide proper snow clearance for the back and left taillight of winter operations vehicles, but fail to provide adequate clearance for the right taillight, as shown in Figure 2-27.

Figure 2-27 Airfoil keeping snow away from the back and left taillights of the winter operations vehicle but unable to keep snow away from right taillights. (NDOT, 2008)

Dinc (2011) conducted practical experiments with side wind deflectors in Nevada; however, the side wind deflectors did not provide the amount of clearance estimated from simulations. This failure appeared to result from the differences between the designed and practical versions due to fabrication and installation process difficulties. Figure 2-28 shows the practical version of the experiment.

Figure 2-28 Side wind deflector on a winter operations vehicle (NDOT Class-15 Snowplow Truck) showing right taillight covered with snow despite the installation of the deflector (Dinc, 2011)

Dur (2007) showed airfoil usage on the back of winter operations vehicles (Sanders) in Alaska, Idaho, Missouri, Montana, New York, South Dakota, and Wisconsin. The California, Colorado, Iowa, Kansas, Kentucky, Minnesota, North Dakota, Orlando, and Vermont DOTs do not use airfoils with their winter operations vehicles. No data was received by call or email from the Illinois, Indiana, Ohio, and Washington State DOTs.

2-7 WIND DEFLECTOR

Wind deflectors are similar to rear airfoils, except they are specifically designed metal flaps placed over taillights to prevent snow accumulation over the lights. Their working principle is the same.

In Alberta, box wind deflectors are mounted above the taillights of the winter operations vehicles. They are designed to hold the rear warning lights free from snow accumulation (Paulichuk, 2005). Figure 2-29 illustrates how the system is installed behind the winter operations vehicles.

Figure 2-29 Side view of a winter operations vehicle showing: (a) Rear airfoil mounted on top of the vehicle and (b)Box wind deflector mounted on top of the taillight (Paulichuk, 2005)

Wind deflectors rarely achieve the same level of performance as airfoils for keeping snow off the taillights. The lights on the right side remain especially susceptible to snow accumulation as seen in Figures 2-30 and 2-31.

Figure 2-30 Wind deflector tests by Alberta Infrastructure and Transportation (Paulichuk, 2005) show extensive snow accumulation on the rear of a winter operations vehicle, despite having wind deflectors over taillights.

Figure 2-31 A direct comparison between the left and right taillights of a winter operations vehicle equipped with box wind deflectors. The right side is more heavily covered than the left side. (Paulichuk, 2005)

Muthumani et al. (2015) found a few agencies using only wind deflectors to decrease the amount of snow, while others mentioned using a combination of wind deflectors with different methods.

To overcome the drawback of box wind deflectors, the research suggests rear airfoils to be installed above the box of the winter operations vehicles in such a manner as to force the flow of air down the full rear width of the vehicle body and be located such that the bottom of the wind deflector is located no more than 300 mm from the top of the raised LED stop, tail and turn lights. However, no such experiments have been conducted to test these recommendations.

2-8 SMART SNOWPLOW SYSTEMS

Smart snowplow systems refer to the technologies used to provide precise information on the conditions of the road around the snowplow trucks. Smart snowplow trucks are equipped with sensors and instruments to avoid collision with other vehicles and obstacles during low visibility caused by blowing snow, fog, and darkness. The smart snowplow system enables operators to perform difficult winter operations in a much safer manner for both the equipment operator and the traveling public (Coffey, 2018).

2-8-1 Minnesota

To determine the recovery time of different roads after snow events, researchers from the University of Minnesota Duluth (UMD) used highway loop detector traffic (MnDOT research, 2018). Rectangular closed wire loops about 6 feet long and 4 feet wide are installed beneath road surfaces of Minnesota, to collect snow accumulation data from the roads. Minnesota Department of Transportation (MnDOT) intends to use the new system along with weather data to relieve snowplow drivers of the burden of estimating the time required to clear roadways and increase the overall efficiency of the fleet (MnDOT research, 2018). The automated system uses data from the wire loops and weather stations to determine normal condition regain time (NCRT) of traffic flow after a snow storm. The system increased the estimation accuracy of road conditions and gave dispatchers a broad view of the traffic flow of the metro area. The research has transformed a computer model into a user-friendly and integrated computer system. The system includes a data management module, a module for target detector station identification and speed recovery function, a module for NCRT estimation, and a map-based user interface that allows dispatchers to generate the estimated NCRT for a specified area. Dispatchers and supervisors can also use the interface to assess traffic flow variations, assign winter operations vehicles, and generate reports for past snow events. The new system directs trucks to harder-hit areas quickly from the nearest station as required (MnDOT research, 2018). Illustration of the system is provided in Figure 2-32.

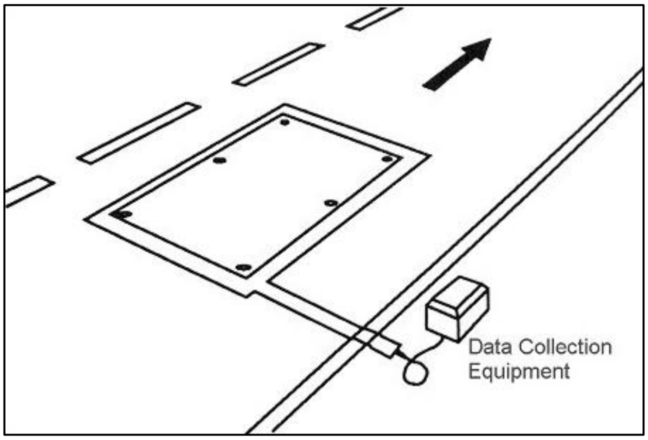


Figure 2-32 Line drawing of a rectangular closed wire loop (6 feet long and 4 feet wide) beneath road surface of Minnesota, used to collect data from the road and direct winter operations vehicles towards harder-hit roadways swiftly through the computer system (MnDOT research, 2018)

The team tested the new integrated system on data gathered from I-494 and I-694 during two snow events in 2015 and 2016. The system was successful in providing consistent and objective estimates of NCRT through utilization of the traffic flow data available from existing detection systems in the metro area. Results generated by NCRTs met or exceeded the accuracy of estimates produced by maintenance personnel (MnDOT research, 2018).

Another research equipped the winter operations vehicles with differential global positioning system (DGPS), geospatial database, and heads-up-display (HUD), which was conducted by a team consisting of 3M (formerly Minnesota Mining and Manufacturing), the University of Minnesota, Altra Technologies, the Minnesota Department of Public Safety, McLeod County, Hutchinson Ambulance, and Federal Highway Administration Research and Technology (FHWA) (Shankwitz & Preisen, 2015). Illustration of a winter operations vehicle equipped with smart safety enhancement devices shown in Figure 2-33.

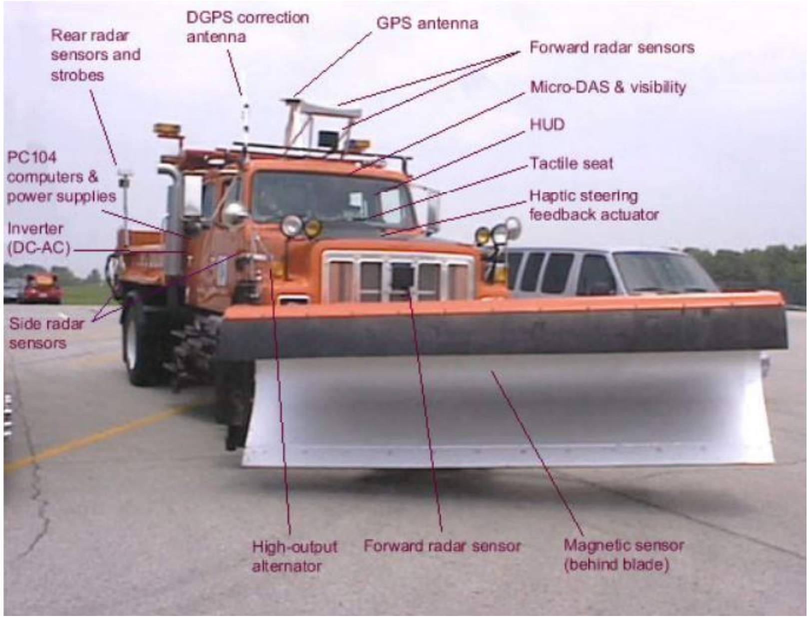


Figure 2-33 A winter operations vehicle of Minnesota DOT installed with equipment for HUD and GPS (Shankwitz & Preisen, 2015)

A differential global positioning system (DGPS) and geospatial database locate fixed objects such as lane boundaries and signposts. Carrier Phase DGPS can be accurate to a two-centimeter level (FHWA, 2001). This precise DGPS, combined with highly accurate geospatial databases (elements of the database are mapped to accuracies of greater than 15 centimeters), provide a high-fidelity means to provide lane-keeping information to a driver. The geospatial database was constructed from several sources, including photogrammetry data and drive-overs by vehicles equipped with highly accurate DGPS and data acquisition equipment. The geo-spatial database is stored in a computer onboard the winter operations vehicles (FHWA, 2001). Collision-avoidance information is sensed by a radar array on the vehicle. By detecting radar signal returns, it determines which objects in the geospatial landscape pose no threat to the driver and which objects do. Only the signals that indicate a threat are provided to the driver through the HUD.

A Magnetic Lateral Warning and Guidance System developed by 3M uses a special magnetic tape to "outline" the lanes on roads (FHWA, 2001). The system’s magnetic pavement marking tape can be used in place of regular lane striping. The tape can either be grooved into the existing pavement and secured with an adhesive or can be underlayed during construction of the road. It is detected by a magnetic sensor on the winter operations vehicle. The sensor indicates the vehicle's lateral position within the lane. The system has a lateral detection range of +/- one meter (approximately three feet), and a vertical detection height of 15 to 45 centimeters (6 to 8 inches) (FHWA, 2001).

A central computer interprets the data from the subsystems to provide an image of what the road would look like if weather conditions were not preventing the driver from seeing it. This image is projected onto a partially reflective, partially transmissive curved piece of ground optical glass that the driver looks through. Developed by the University of Minnesota, the Heads Up Display (HUD) flips down much like a sun visor so that it can be used when needed and placed out of the way when visibility is not bad enough to warrant its use (FHWA, 2001). Using the HUD, the driver can see the lane boundaries projected onto the snow-covered roadway and can see the location of obstacles that impede safe travel. Looking through the HUD, the driver focuses about nine meters (30 feet) in front of the winter operations vehicle, which is normal for most drivers (FHWA, 2001).

To ensure safety, all of the subsystems have backups. Multiple radar devices are used so that if one radar is not operating, another one can take its place and transmit the required data. One assumption is that real-time DGPS communication will not be available all the time because the link between the winter operations vehicle and the DGPS satellite will fail (FHWA, 2001). Although the latest DGPS receivers re-acquire lock in 10 to 15 seconds, this is more than enough time for a winter operations vehicle performing snow-removal operations to go off the road or cause a collision. However, inertial measurement provides guidance during the loss of satellite lock while also providing vehicle-orientation information (FHWA, 2001). Figure 2-34 shows a winter operations vehicle equipped with HUD.

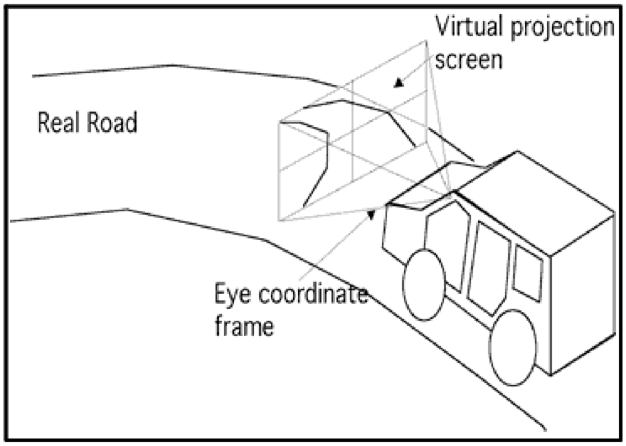


Figure 2-34 Schematic drawing of working principle of HUD (left), and HUD installed on a winter operations vehicle of Minnesota (right) (Shankwitz & Preisen, 2015)

During the winters of 2000 and 2001, thirteen snowplow operators successfully completed a 5-mile long driving course with the windshields covered (FHWA, 2001). The drivers liked the combination of visual, auditory, and haptic lane departure warnings. Along the straight segments, the lane departure warnings were rarely deployed. On the challenging corners (when the HUD image disappeared), drivers used the auditory and haptic lane departure warnings to successfully guide them through the turns (Shankwitz & Preisen, 2015).

Initially, the HUD used on Minnesota's test snowplows presented all road markings in a monochromatic yellow (FHWA, 2001). Through interviews between the snowplow operators and researchers, color coding was added to provide more assistance to the operators.

2-8-2 Nova Scotia

In Nova Scotia, an online website called "Plowtracker" shows the winter maintenance activities taking place on provincially owned and maintained roadways (Transportation and Infrastructure Renewal, 2018). Plowtracker shows the location of the winter operations vehicles operating during the winter season. It also allows the user to turn on other information such as the provincial winter maintenance service levels, access to the provincial highway cameras, and the ability to see where winter maintenance activities have taken place within the last 30, 60, and 90 minutes. Figure 2-35 shows the Plowtracker website.

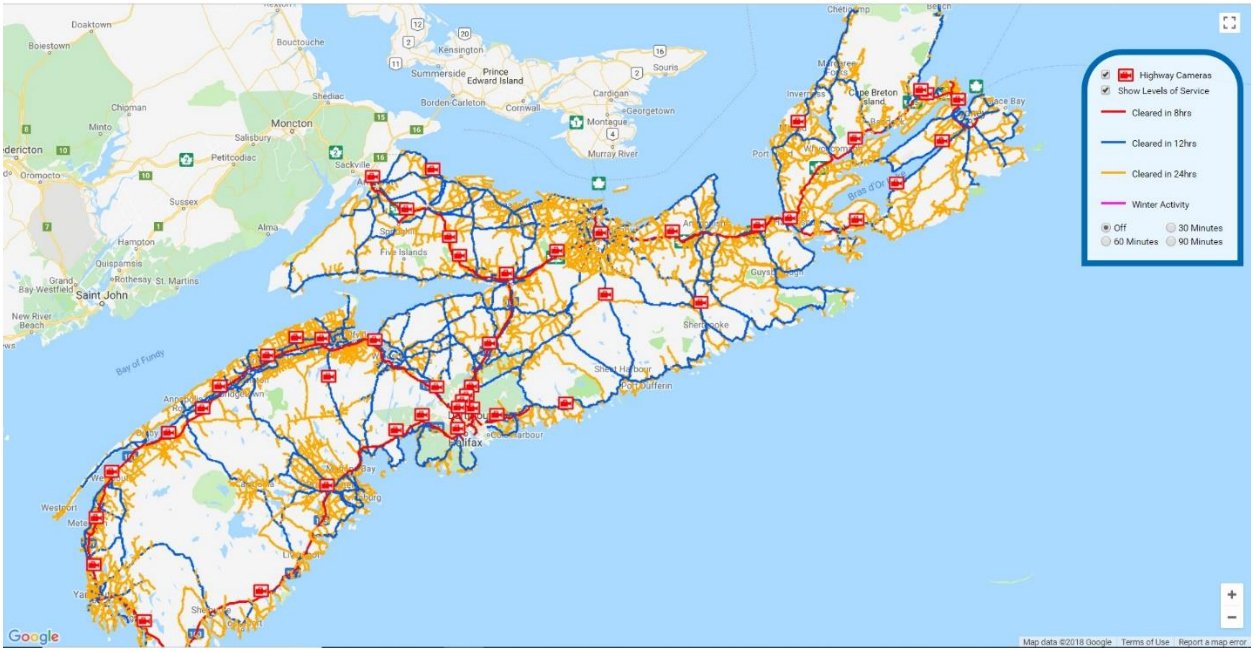


Figure 2-35 Plowtracker website showing various winter operation details in Nova Scotia (Transportation and Infrastructure Renewal, 2018)

2-8-3 Pennsylvania

Pennsylvania Department of Transportation (PennDOT) uses a “511 Pennsylvania snowplow tracker system” to give users access to current road conditions (NBC, 2017). It shows the locations of snowplow trucks and allows users to track their routes. The snowplow icons do not move in real time, but refreshing the page updates their current location. The tracker is available via an app for smartphones, called the “511PA mobile app”. Image of tracker shown in Figure 2-36.

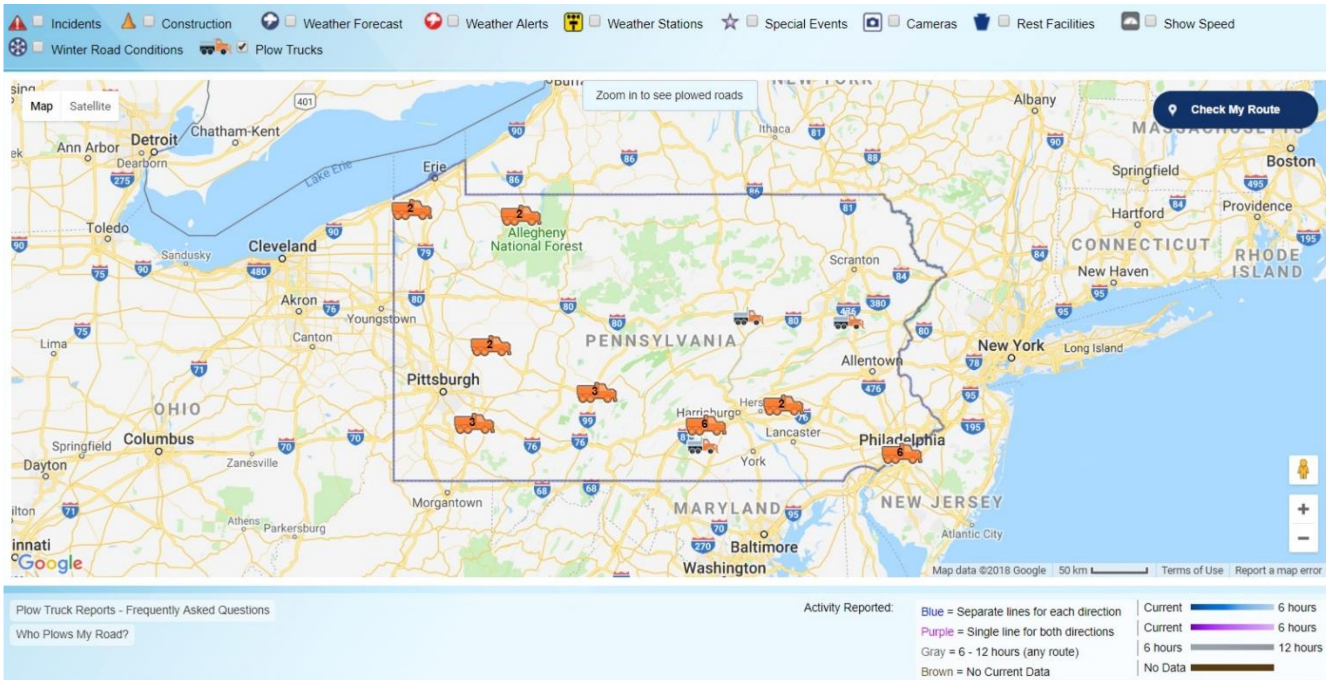


Figure 2-36 "511 Pennsylvania snowplow tracker system" showing the locations of snowplow trucks their past routes (511PA, 2018)

2-8-4 Connecticut

In Windsor, Connecticut, residents can check online to see where winter operations vehicles have been working. The website service shows where the operations vehicles have traveled in the last two hours. Information on the site is delayed by approximately 30 minutes. The activity of the fleet during the previous week is available to download every Monday (CBC News, 2017).

2-8-5 Chicago

In Chicago, snowplow tracking data is open to the public via the free app "Plowtracker". The app shows winter operations vehicle routes all over the city, and provides a clear understanding of the roads that have been plowed and the roads that will be plowed after a snow storm. The information increases the safety of travelers as they are aware of the dangers of the roads before initiating travel. Chicago and New York introduced the app in early 2012, followed by Seattle, Maryland, and Virginia (Daily Reporter, 2015).

2-8-6 Washington DC

In Washington, DC, the District's Automated Vehicle Locator (AVL) system is used to update the locations of winter operations vehicles of DC throughout the city (District Snow team, 2018). The system shows where vehicles have been within the last 12 hours (these streets will appear blue on the map) and where they were more than 12 hours ago (these streets will appear gray on the map). It also shows weather information, key points about the snow/ice removal program, and DC traffic camera views. The system can be accessed from smartphones and tablets, as well as from laptops and desk computers. A picture showing the mapping system of AVL is shown in Figure 2-37.

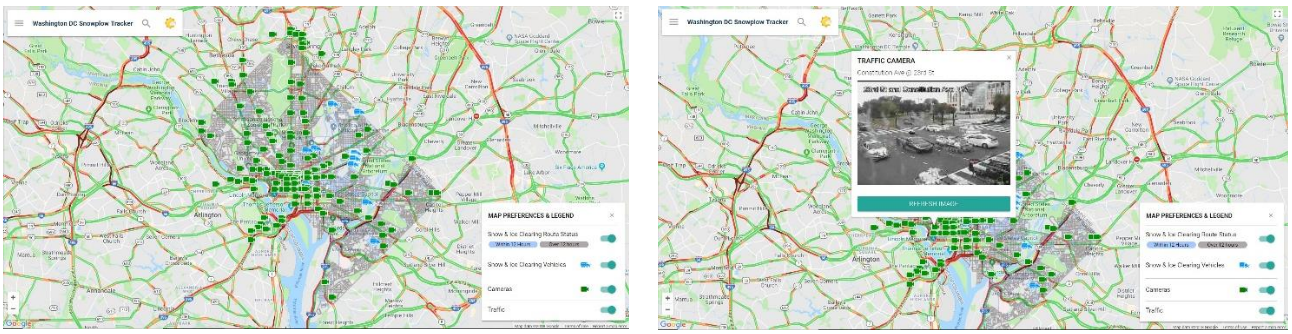


Figure 2-37 District's Automated Vehicle Locator (AVL) system in Washington DC showing the locations and traffic camera views of winter operations vehicles of DC (District Snow Team, 2018)

2-8-7 Michigan

The Michigan Department of Transportation (MDOT) has GPS tracking information for winter operations vehicles in its MI Drive website (MI drive, 2018). Information regarding winter operations is available for MDOT's Southwestern region including Berrien, Branch, Calhoun, Cass, Kalamazoo, St. Joseph, and Van Buren counties. The winter operations vehicles are displayed on the map when they move faster than ten miles per hour (MPH) within 50 feet of the roadway. Information is also provided when a winter operations vehicle is down or when salt is being spread. On some of the winter operations vehicles, cameras are available for those who wish to get a first-hand look at conditions in front of the vehicle. MDOT has been using GPS tracking with their winter operations vehicles for the past few years. With over 80 winter operations vehicles and 140 vehicle operators, MDOT's MI Drive website assists motorists to travel more efficiently across the State of Michigan in snowy road conditions (Fox 17 West Michigan, 2015). Figure 2-38 and Figure 2-39 show the interface of MI Drive website.

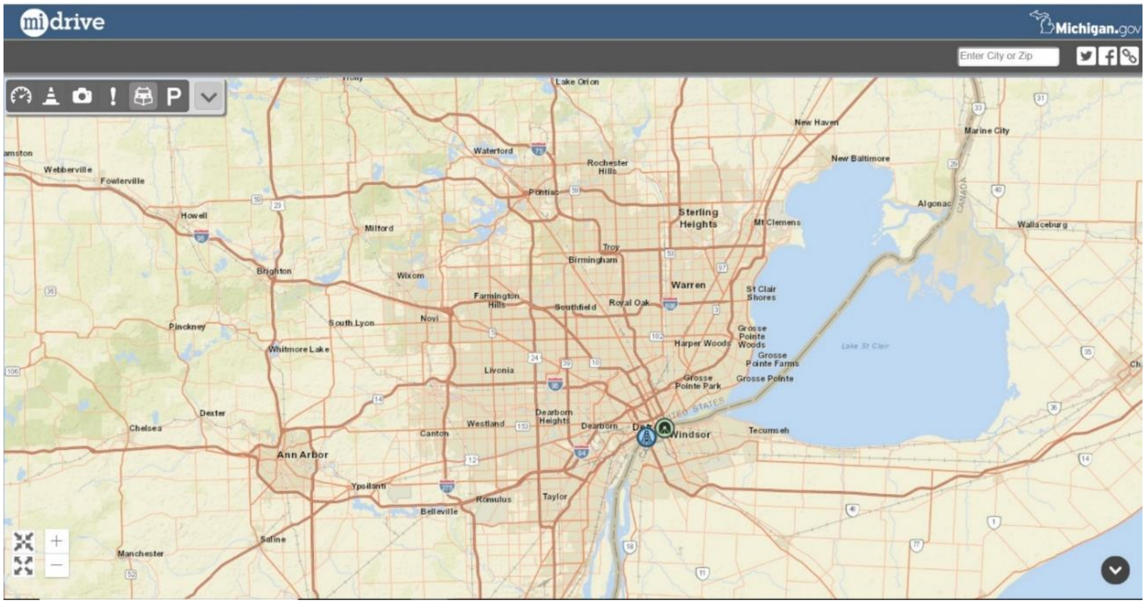


Figure 2-38 Interface of MDOT's MI Drive website (MI Drive, 2018)

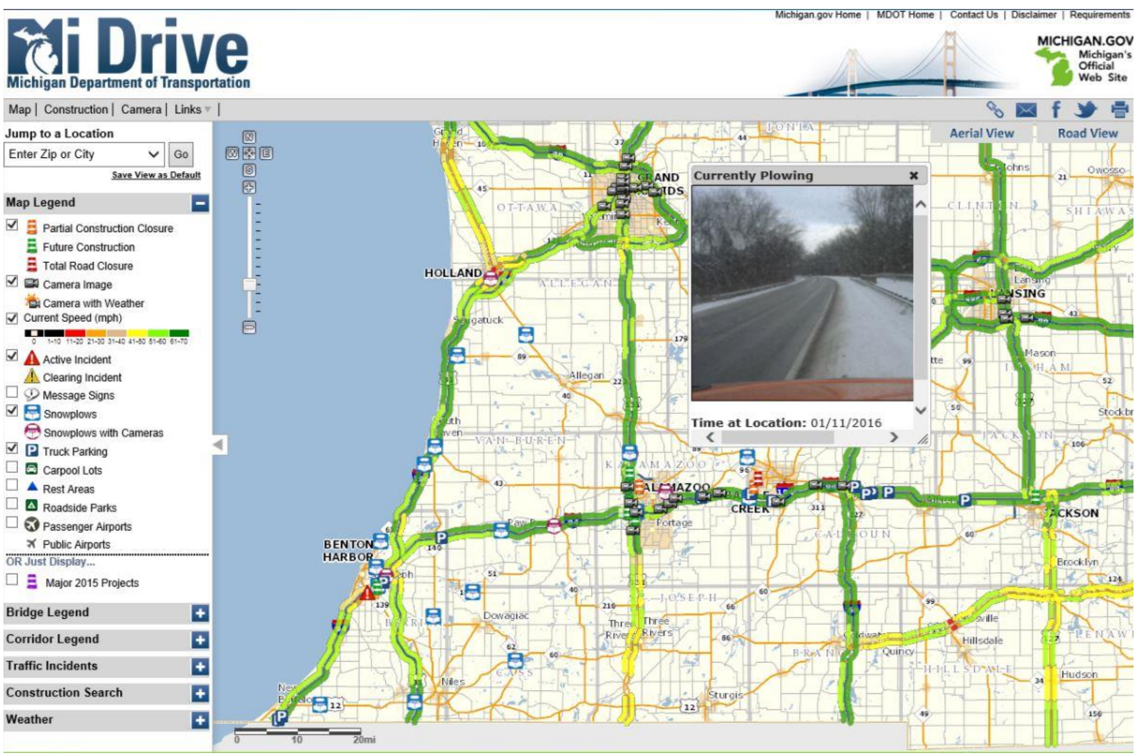


Figure 2-39 Interface of MDOT's MI Drive website showing camera view of an active winter operations vehicle (Cook, 2016)

In Saginaw County (Michigan), the public can view snowplowing progress during a storm using the "Saginaw County Road Commission's Plow Locator" (Esri, 2014). The online tracking system is hosted by Esri ArcGIS. The ArcGIS Server and ArcGIS Online provide a portal that offers real-time map displays of winter operations. The locator allows the people of Saginaw County to follow the route of winter operations vehicles on laptops, smartphones, or desktops. It shows whether a road is open or impassable, as well as the primary roads scheduled to be cleared first after a snow storm, and whether plow blades are up or down. The map is updated every 10 hours (Esri, 2014).

2-8-8 North Dakota

The City of Minot, North Dakota, has attached GPS chips to its vehicles involved with winter operations. All information of winter operations information are available on the "City of Minot" website provided by Razor tracking (Razor tracking, 2018). It is accessible by cellphones or computers and shows where the winter operations vehicles are at the moment (Minot news, 2017). Figure 2-40 shows the "City of Minot" website for information regarding winter operations.

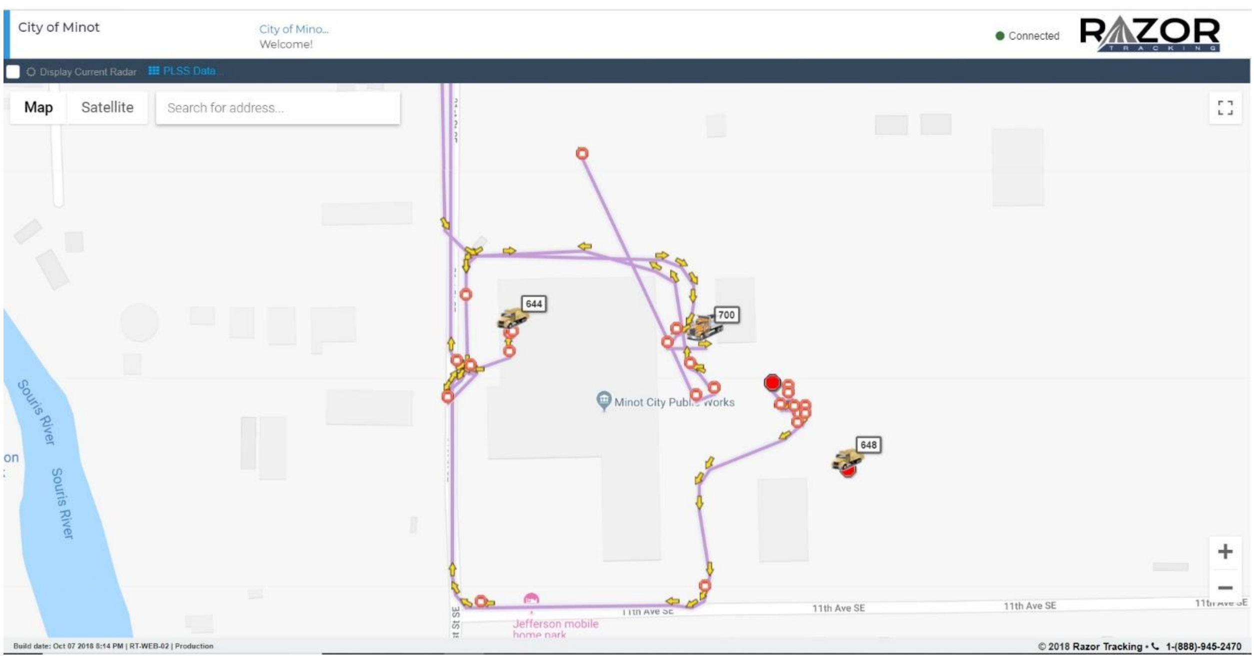


Figure 2-40 City of Minot website for information regarding winter operations (Razor tracking, 2018)

2-8-9 New York

The City of Rochester (New York) uses "PlowTrax" (similar to "Plowtracker"), a web-based map, to update the location of their winter operations vehicles during snow events using GPS. The City tracks the progress of approximately 150 winter operations vehicles, and show their current locations and updates the map every five minutes during snow events. The locations of each vehicle that is currently in use are shown as truck symbols. Plow operations in residential streets can be observed by clicking "Residential plow routes" on the map. This option enables the viewer to see the group of streets serviced by each winter operations vehicle (PlowTrax, 2018).

2-8-10 California and Arizona

California and Arizona developed the "Advanced Snowplow Driver Assistance System" (ASP) for safer winter weather operations (FHWA, 2001). ASP, also known as RoadView™, used intelligent vehicle systems, advanced vehicle controls and safety systems (AVCSS) technologies to provide winter operations vehicle operators with highly accurate views of where the vehicle is and a prediction of where it will be (FHWA, 2001). Major ASP components include a main computer, a human/machine interface (HMI) with a visual display. Some of the worst visibility conditions during winter could be overcome with the aid of ASP cab-mounted display. The system received data from snowplows' collision-warning system that was installed on the vehicles. Radar sensing assisted drivers to find the road and obstacles that could be in the way of the plow (FHWA, 2001). An ASP setup is shown in Figure 2-41.

Figure 2-41 ASP Human-Machine Interface is mounted on the windshield of a Caltrans snowplow (FHWA, 2001)

2-8-11 Texas

The Texas Department of Transportation (TxDOT) uses "Networkfleet" system provided by Verizon to track their winter operations vehicles during winter operations. The system combines GPS fleet management hardware and online software. TxDOT employees receive tracking data on their desktop computers, and they can track the winter operations vehicles deployed at the current time (Dahl, 2018).

2-9 LASER GUIDED SNOWPLOWS

Lasers can be used to guide winter operations vehicle operators about the extremities of their operations equipment in order to avoid hitting any obstacles in their path. Sharp and focused laser guides provide unique assistance when operating in very low visibility winter conditions.

The Iowa Department of Transportation has installed specially designed laser-guidance devices on half-dozen winter operations vehicles statewide (Laserline, 2018). The technology is designed to remove snow more precisely and eliminate damage caused by traditional wing plows, which can bump into mailboxes, signposts, bridge abutments, and other obstructions. The technology works by using a laser located above the cab of the vehicles and shoots a green beam about 60 feet ahead of the vehicles' wing plow (Laserline, 2018). It alerts the winter operations vehicle operator about the precise location of the wing plow blade as it clears snow on the road. State officials said the device appears particularly useful for inexperienced drivers and drivers who may be tired at the end of a long, 12-hour shift. The equipment has been provided by Laserline Mfg., Inc., Oregon. The Iowa Department of Transportation bought the laser-guided winter operations equipment during the winter of 2007, but it did not arrive in time for a full statewide test. Pictures of the devices and their application are provided in Figures 2-42, 2-43, 2-44 and 2-45 (Laserline, 2018).

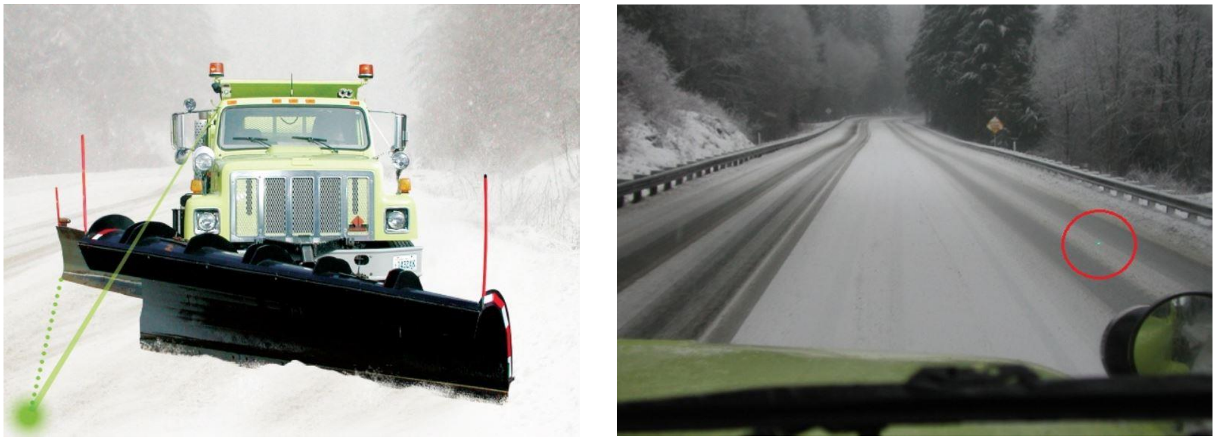


Figure 2-42 Laser path guidance system illustration and actual laser projection on the road from a winter operations vehicle (Laserline, 2018)

Figure 2-43 Two different winter operations vehicles with laser projection equipment installed on them (Laserline, 2018)

Figure 2-44 Laser control box inside of vehicles (Laserline, 2018)

Figure 2-45 Laser projection in action showing outside edge of wing plow of a winter operations vehicle (Laserline, 2018)

In Fargo, North Dakota, the laser-guided system alerts winter operations vehicle operators of mailboxes, curbs and other obstacles. The winter operations vehicle operators feel more comfortable and confident following the laser guides in front of them for operating their wing plows, rather than taking their eyes off the road to check their rear view mirrors and increasing chances of collisions with other vehicles ahead of them (West Fargo Pioneer, 2016). The City of Fargo sometimes employ a second driver in order to safely operate the wing plows at the back. Laser guides eliminate the need for any additional drivers on a single winter operations vehicle. During operations, a laser provides an extra set of eyes to avoid hitting cars, people and other obstacles. The City of Fargo has them on eight snowplow trucks. As of December 2016, the City of Moorhead purchased a new truck equipped with a laser-guided system (West Fargo Pioneer, 2016).

In North Virginia, winter operations vehicles were equipped with a laser beam that helps guide the vehicle operators keep away from hitting mailboxes. Many mailboxes have been toppled by snowplow blades in past snow removal operations (Northern Virginia Daily, 2015). Figure 2-46 shows a laser mounted on top of a snowplow truck.

Figure 2-46 Bright green laser, as a guide to the trailing edges of snowplow trucks' wing plows, mounted on top of the trucks (Northern Virginia Daily, 2015)

2-10 SUMMARY

Table 2-5 summarizes the methods and devices to enhance the safety of winter operations vehicles during winter weather operations based on the literature review.

Table 2-5 Evaluation of Methods and Devices for Safety Applications in Winter Weather Operations

<table>
<tr><th colspan="3">Methods and Devices</th><th>U.S. State and Canada Provinces</th><th colspan="2">Advantages</th><th colspan="2">Disadvantages</th><th>References</th></tr>
<tr><td rowspan="6">1. Warning Lights</td><td rowspan="5">Light Emitting Diode (LEDs)</td><td>Amber /Yellow LED Light</td><td>Texas, Alaska, Ohio, Indiana, Minnesota, South Dakota, Illinois, Iowa, Kansas, Maryland, Gorgias</td><td rowspan="5">Long services life, increased reliability, compacted design, high efficiency, low heat production, high brightness</td><td>Good visibility in dark and fog</td><td rowspan="5">Reducing the appearance of off angels; Not Generating enough heat to melt snow</td><td>Not reflect the severity level of hazardous situation</td><td rowspan="5">TxDOT (2017); Muthumani et al. (2015); Howell (2015); USA Today (2015); City of Winnipeg (2012); McCullouch and Stevens (2008);</td></tr>
<tr><td>White LED Light</td><td>Ohio, South Dakota, Iowa</td><td>---</td><td>Low fog penetration</td></tr>
<tr><td>Blue LED Light</td><td>Alaska, Minnesota, Texas, Iowa</td><td>---</td><td>Low fog penetration</td></tr>
<tr><td>Red LED Light</td><td>South Dakota, Georgia</td><td>High visibility in dark and fog</td><td>---</td></tr>
<tr><td>Green LED Light</td><td>Ohio, North Dakota</td><td>---</td><td>---</td></tr>
<tr><td colspan="2">High Intensity Discharge (HID)</td><td>Massachusetts, Minnesota, Washington</td><td colspan="2">Producing enough heat to melt snow</td><td colspan="2">Consuming more energy than LED lights</td><td>Howell (2015)</td></tr>
<tr><td colspan="3">2. Heated lens</td><td>Nevada, North Dakota</td><td colspan="2">Melting the mass of snow on the lens.</td><td colspan="2">Creating a cupola of ice over the lights</td><td>Muthumani et al. (2015)</td></tr>
<tr><td colspan="3">3. Message Signs</td><td>California, Minnesota, Ohio, Pennsylvania, Michigan, New Jersey, Kentucky and Kansas</td><td colspan="2">Conspicuous markings offer better visibility of the winter operations vehicles to any vehicles coming from behind</td><td colspan="2">Has to be kept clean regularly</td><td>WITF (2019); (MTO, 2018); Caltrans (2018); TxDOT (2017); KDOT (2017); Caltrans (2017); Star Tribune (2017); MTO (2015); Muthumani et al. (2015); Province (2014); Lake News (2012); New Jersey Herald (2012); Saginaw News (2012); ODOT (2011); USDOT (2001)</td></tr>
</table>

Methods and Devices	U.S. State and Canada Provinces	Advantages	Disadvantages	References
4. Retroreflective markings	Iowa, Virginia, Alberta (Canada), Ontario (Canada), New Brunswick (Canada), Pennsylvania, Indiana and Connecticut	Increase the visibility of winter operations vehicles at night and low visibility conditions; Easy to install; No need for wiring or specially designed surfaces	Keeping it clear of snow and dirt is difficult	SNC Lavalin O&M (2018); ODOT (2018); Daily American (2017); CTC & Associates LLC, (2016); Muthumani et al. (2015); Washington Top News (2015); CT Mirror (2015); Barbaccia, T. G. (2014); Dow & Pearsall (2014); McCullouch and Stevens (2008); CTRE (2006); Paulichuk (2005); NHTSA (2001)
5. Rear Airfoil	Alaska, Idaho, Missouri, Montana, New York, South Dakota, Wisconsin, Nevada (Canada)	Keeping snow off the rear of the winter operations vehicles; Eliminating the time needed by operators to clean off the snow	Does not provide adequate clearance of snow for right taillight	Dinc (2015); NDOT (2008); Dur (2007)
6. Wind Deflector	Alberta (Canada), Minnesota	Prevent snow accumulation over taillights	Does not provide adequate snow clearance when used solely	Muthumani et al. (2015); Paulichuk (2005)
7. Smart Snowplow Systems	Texas, Minnesota, Neva Scotia (Canada), Pennsylvania, Connecticut, Chicago, Michigan, Washington DC, North Dakota, New York, California and Arizona	Latest technologies improve accuracy and visibility of winter operations vehicle operators; Avoids collisions with other vehicles and obstacles during low visibility conditions	Equipment are expensive	Transportation and Infrastructure Renewal (2018); 511PA (2018); District Snow Team (2018); MI Drive (2018); Coffey (2018); City of Minot (2018); City of Rochester (2018); MnDOT research (2018); Dahl (2018); CBC News (2017); Minot News (2017); NBC (2017); Cook (2016); Daily Reporter (2015); Fox 17 West Michigan (2015); Shankwitz & Preisen (2015); Esri (2014); Pittman (2012); FHWA (2001);
8. Laser Guided Snowplows	Iowa, North Dakota and North Virginia	Guide winter operations vehicle operators about the extremities of their plowing equipment and avoid hitting any obstacles in their path	Equipment are expensive	Laserline (2018); West Fargo Pioneer (2016); Northern Virginia Daily (2015); USA Today (2011)

CHAPTER 3
DISTRIBUTION OF SURVEYS AND ACCUMULUATION OF SURVEY RESPONSES

A survey questionnaire was designed to identify the current state of safety applications in winter weather operations. The first draft of the survey was submitted to the TxDOT Research and Technology Implementation (RTI) technical panel for review. The survey questionnaire was revised and finalized based on the comments received from the technical panel. The research team used “Qualtrics.com” as an online platform to conduct the survey for this research project. The printable formats of the final survey design are presented in Appendix B and C. The survey was distributed amongst the Directors of Maintenance in all TxDOT districts, as well as to other state DOTs throughout the United States (U.S.). To distribute the survey, an invitation email along with the online link to the survey was sent to survey respondents. The drafts of the invitation emails are presented in Appendix D and E.

3-1 SURVEY QUESTIONNAIRE STRUCTURE

The survey questionnaire sought to capture the most important information about safety applications in winter weather operations of different TxDOT districts and various states other than Texas. The questionnaire starts with a brief description of the project and an instruction on how to complete the survey. The section for contact information collects the names, locations and email addresses of survey respondents, which was used for future follow-up interviews. The section for general information inquires about the usage of shadow vehicles and collects images of winter operations vehicles used by different DOT offices. The following sections collect safety application information regarding warning lights, heated lens, message signs, retroreflective markings, rear airfoil, wind deflectors, and smart snowplow systems. All the sections are designed in a way that the respondents quickly pass through the safety applications that they have no experience of using. The last section asks if the respondents are willing to participate in follow-up interviews to collect further information.

3-2 ACCUMULATION OF SURVEY RESPONSES

Twenty individuals in TxDOT and 10 individuals outside Texas have responded to the survey. The TxDOT respondents are from 15 different TxDOT districts: Abilene, Amarillo, Atlanta, Austin, Bryan, Dallas, Lubbock, Lufkin, Odessa, Paris, Pharr, San Antonio, Tyler, Waco and Wichita Falls. The ten respondents from outside Texas represent ten states: California, Indiana, Iowa, Kansas State, Massachusetts, Missouri, New York, North Dakota, Oregon and Utah. The research team combined the responses whenever more than one individual responded from a district (in Texas) or a state (outside Texas). The following sections present a descriptive analysis of the information collected so far.

3-2-1 Contact Information

The first section collects the contact information and location of survey respondents. Figure 3-1 illustrates the locations and positions of respondents in their respective TxDOT districts. Responses were collected from 15 districts of Texas.

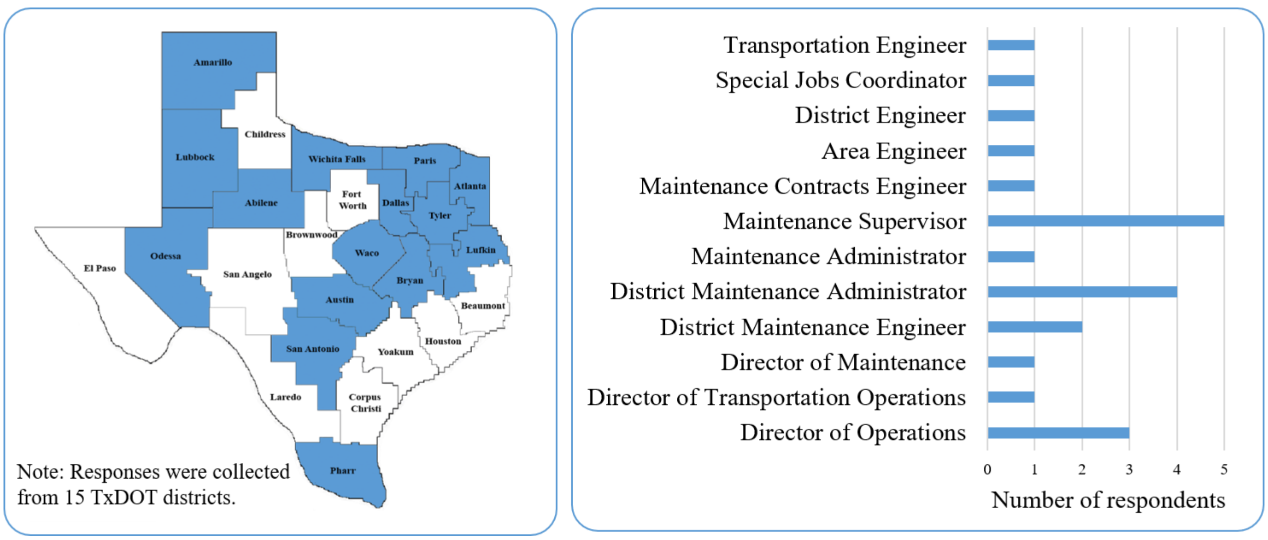


Figure 3-1 Locations (left) and positions (right) of survey respondents in Texas

Figure 3-2 shows the locations and positions of respondents from the ten states other than Texas.

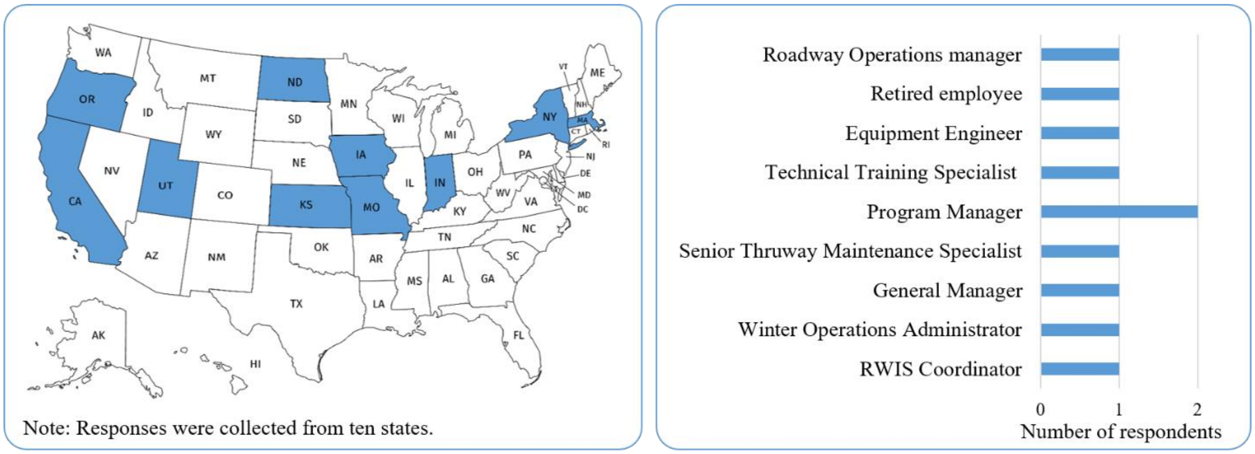


Figure 3-2 Locations (left) and positions (right) of survey respondents in ten states other than Texas

3-2-2 General Information

Figure 3-3 shows whether different TxDOT districts use shadow vehicles.

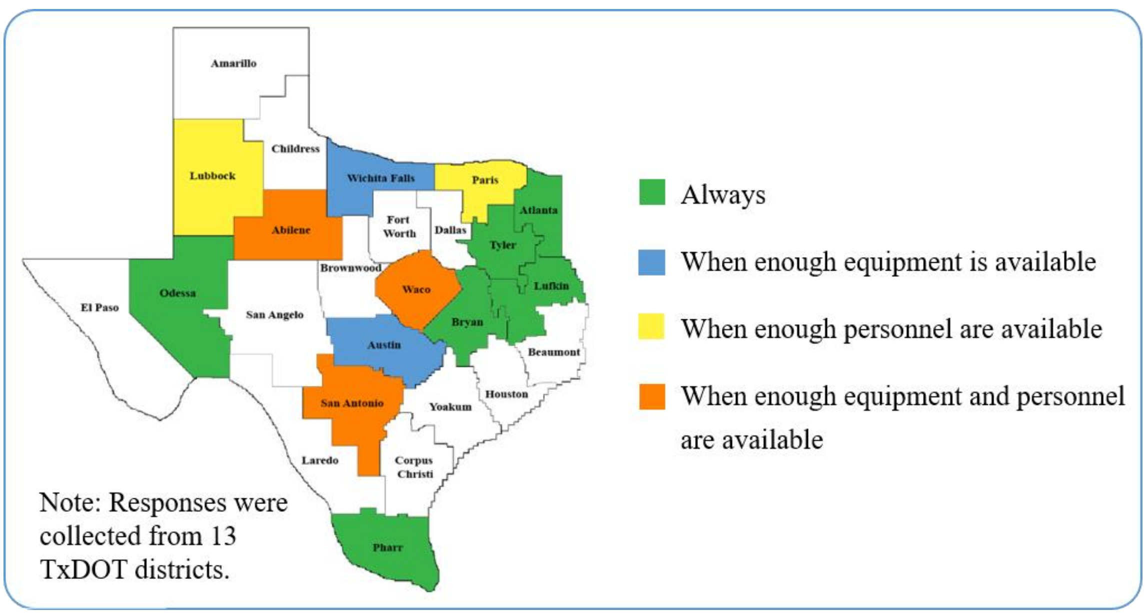


Figure 3-3 Shadow vehicle usage in different TxDOT districts

Figure 3-4 shows whether the nine states other than Texas use shadow vehicles.

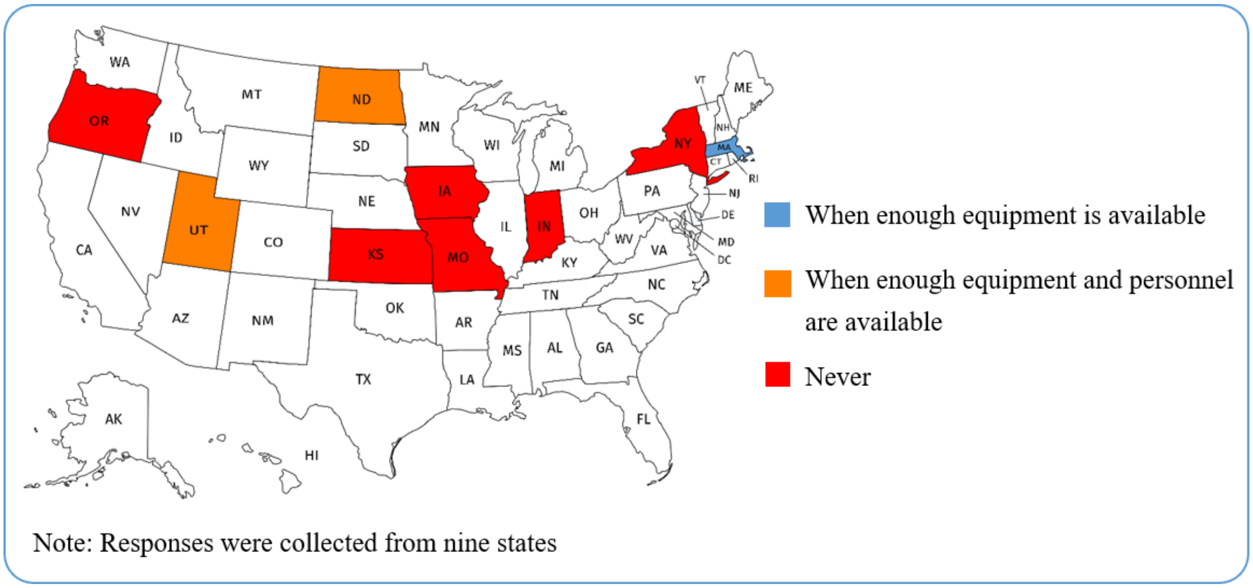


Figure 3-4 Shadow vehicle usage in nine states other than Texas

This section also asks respondents for images of winter operations vehicles used by their district offices. Pictures of winter operations vehicles used in the Paris and Wichita Falls districts of Texas along with operations vehicles of Indiana, Iowa, Kansas, North Dakota, Oregon and Utah are shown in Figures 3-5, 3-6, 3-7, 3-8, 3-9, 3-10, 3-11, 3-12, 3-13 and 3-14, respectively.

Figure 3-5 Back view of a winter operations vehicle of TxDOT Paris District

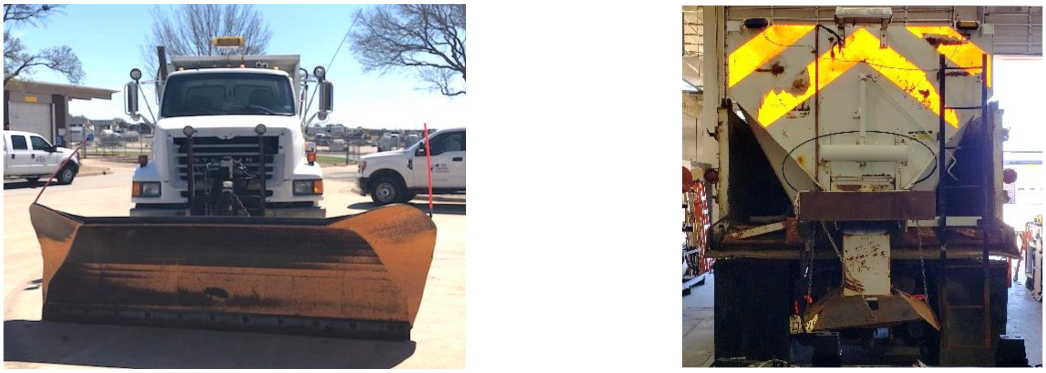


Figure 3-6 Front (left) and back (right) views of winter operations vehicles of TxDOT Wichita Falls District

Figure 3-7 Front view of winter operations vehicles of Indiana

Figure 3-8 Back view of winter operations vehicles of Indiana

Figure 3-9 Front (left) and back (right) views of winter operations vehicles of Iowa

Figure 3-10 Front (left) and back (right) views of winter operations vehicles of Kansas

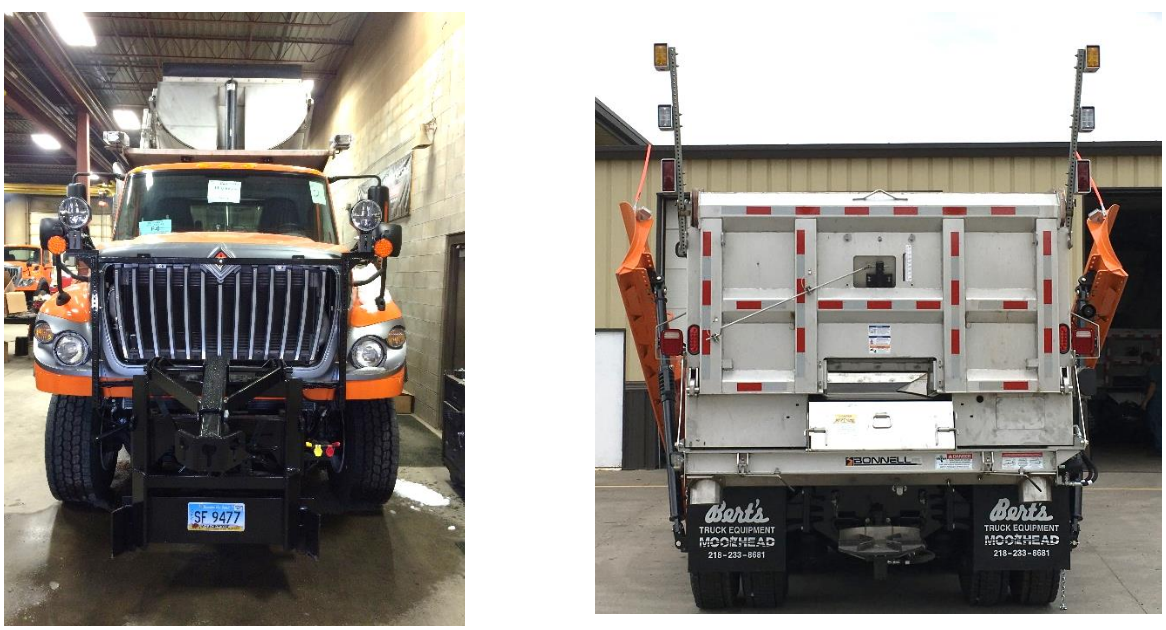


Figure 3-11 Front (left) and back (right) views of winter operations vehicles of North Dakota

Figure 3-12 Back view showing wing plows of winter operations vehicles of North Dakota

Figure 3-13 Front (left) and back (right) views of winter operations vehicles of Oregon

Figure 3-14 Back view showing wing plows of winter operations vehicles of Utah

3-2-3 Warning Lights

Survey results from the 15 TxDOT districts on the evaluation of warning lights are summarized in Figure 3-15. Eleven districts use amber-blue colored warning lights, while the others use amber color lights only or alternations of amber and blue colored lights on their vehicles. Ten districts have restrictions on the use of some colors for warning lights. The types, locations of installation and patterns of warning lights are also investigated.

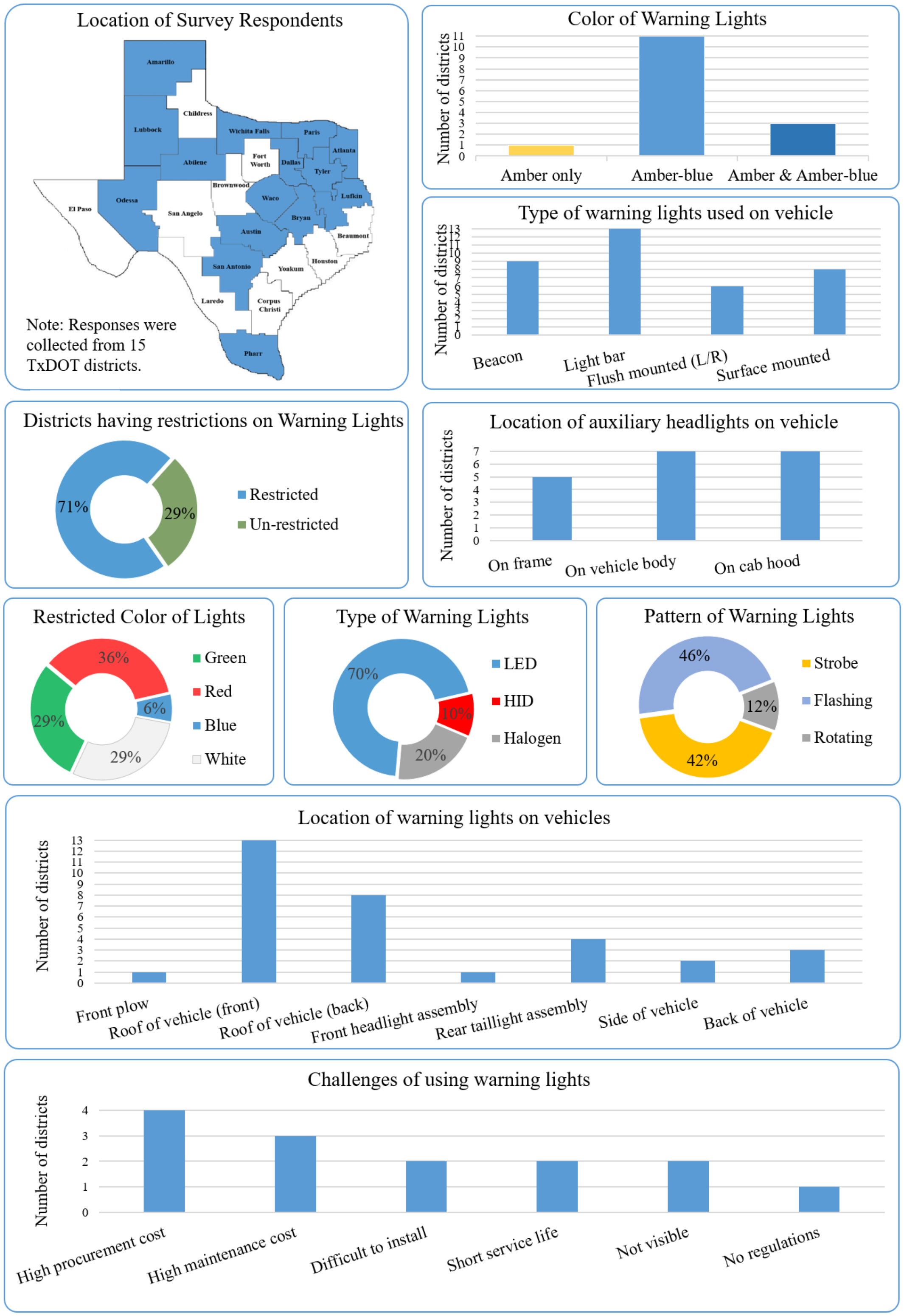


Figure 3-15 Survey results of 15 TxDOT districts on the evaluation of the warning lights on winter operations vehicles

The survey results from the ten states other than Texas on the evaluation of warning lights are summarized in Figure 3-16. Significant differences in warning lights between Texas and the rest of the U.S. occur in terms of color and type of warning lights. Texas predominantly uses amber-blue colored lights with a bar type installation, while the rest of the U.S. mostly use amber colored lights with flush and surface mounted installations.

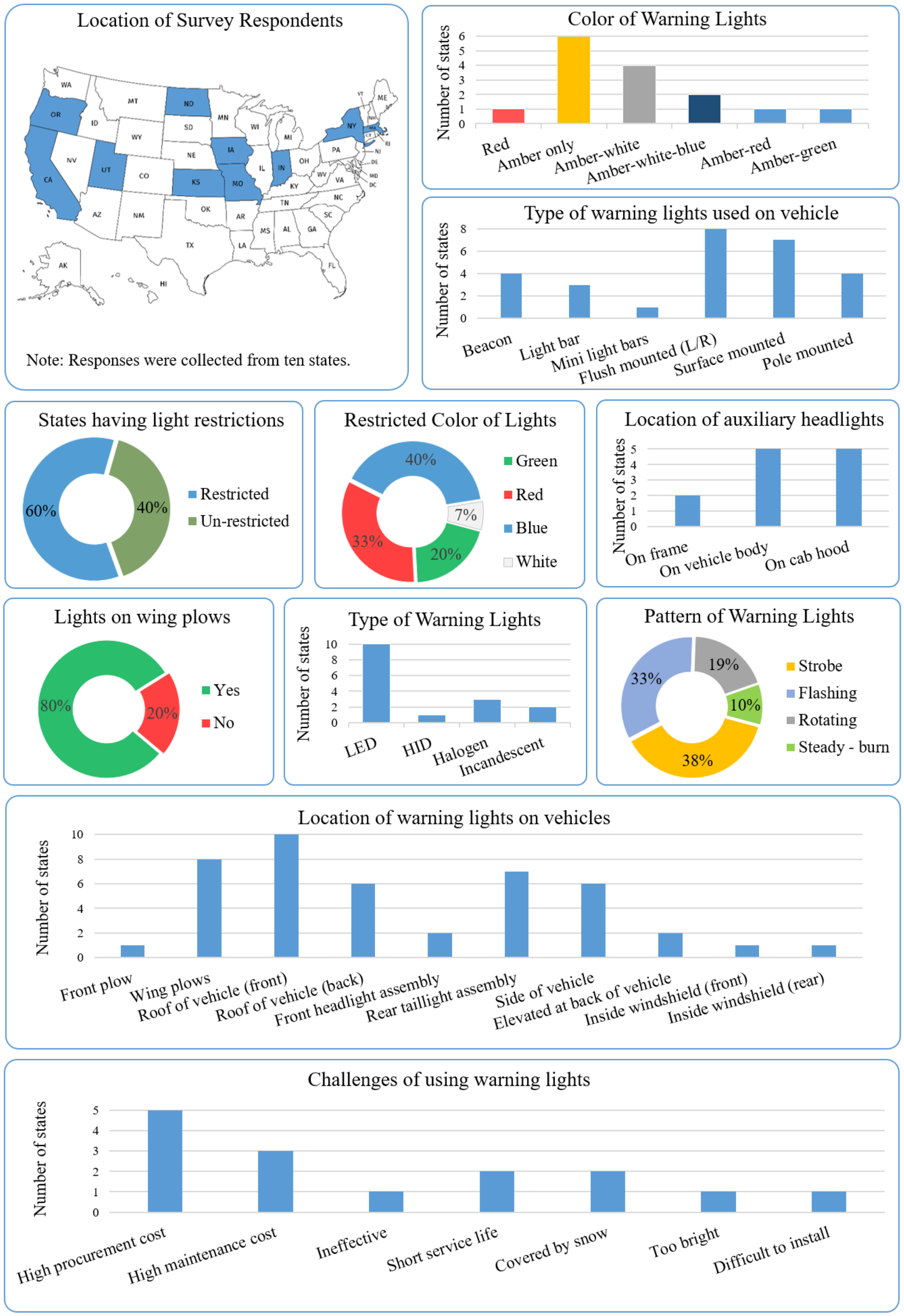
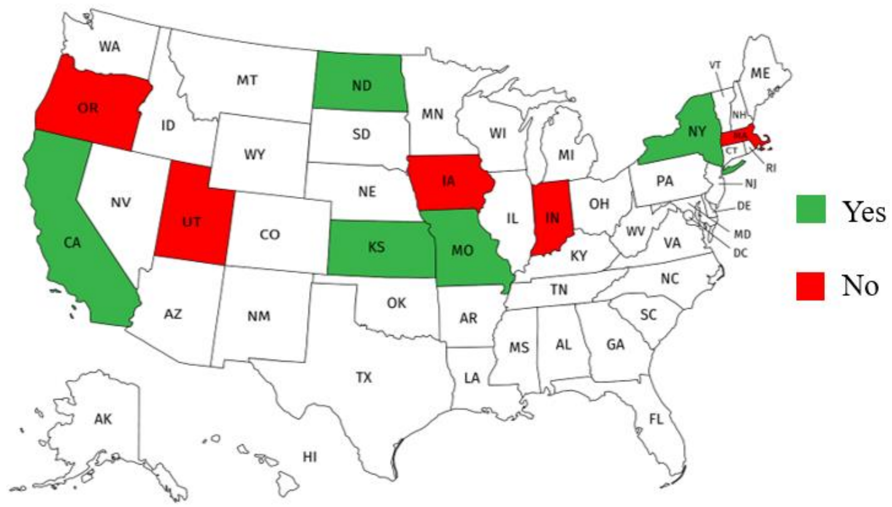


Figure 3-16 Survey results of the ten states other than Texas on the evaluation of warning lights on winter operations vehicles

3-2-4 Heated Lens

Responses from 12 TxDOT districts and ten states other than Texas were collected in this section of the survey. None of the TxDOT districts use heated lens as safety applications during winter weather operations. The respondents from California, Kansas, Missouri, New York and North Dakota have reported using heated lens (Figure 3-17). The respondents from California and New York reported the high procurement cost of the lens as a challenge. Kansas and Missouri respondents have recently implemented the method and are unable to report any challenges.



Note: Responses were collected from ten states.

Figure 3-17 Use of heated lens in ten states other than Texas

3-2-5 Message Signs

Responses from 15 TxDOT districts were collected in this section of the survey and summarized in Figure 3-18. A majority of the message signs in Texas are installed on the back of the plows, and use black text on yellow backgrounds. One of the TxDOT districts (San Antonio) reported using digital message signs on their winter operations vehicles.

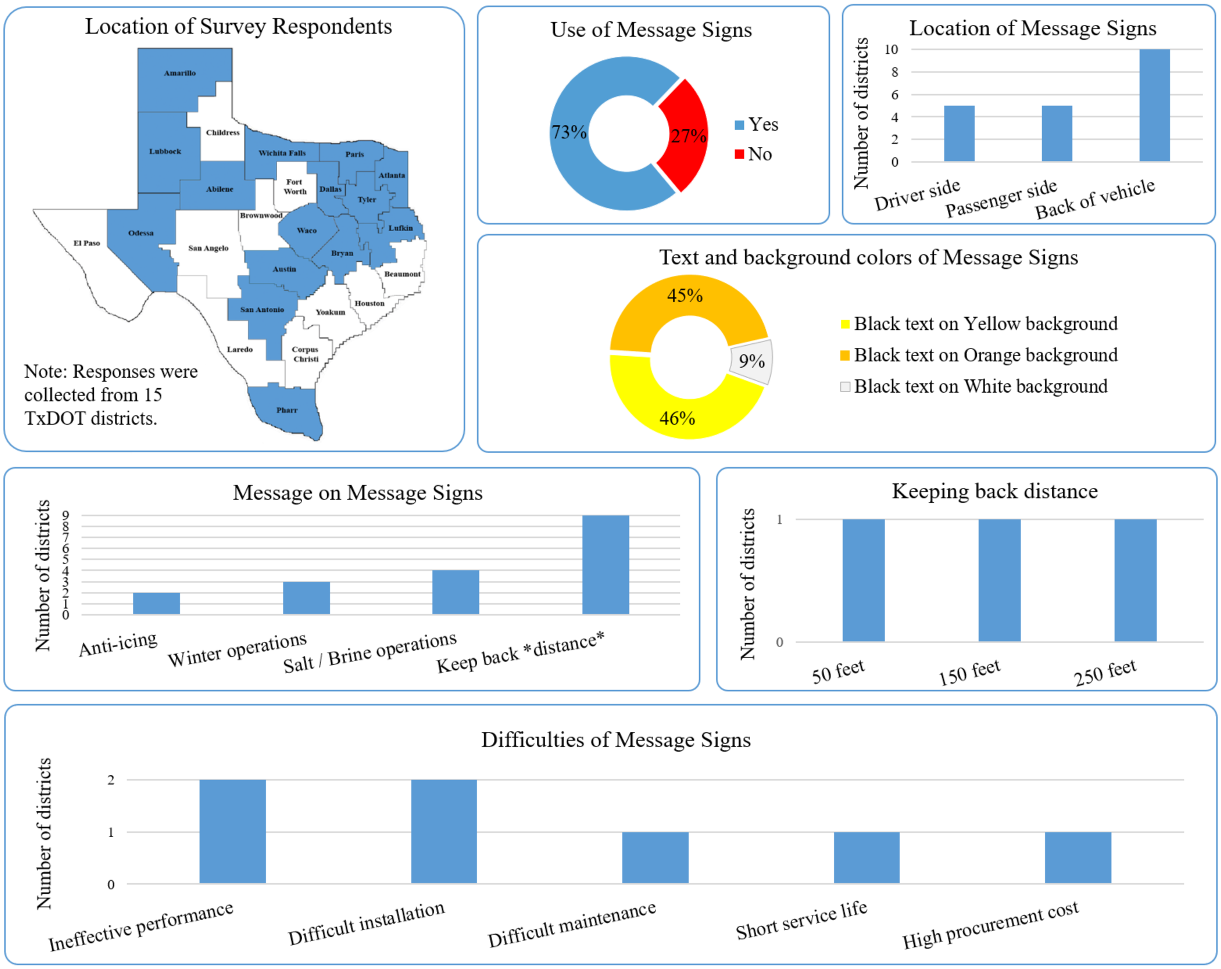


Figure 3-18 Survey results of 15 TxDOT districts on the evaluation of message signs of winter operations vehicles

Responses from ten states other than Texas were also collected in this section of the survey and summarized in Figure 3-19. A majority of the message signs of both Texas and the other states are installed on the back of the plow. None of the survey respondents of TxDOT districts reported using variable message signs on roads, but seven states other than Texas use them to convey winter warning messages to commuters.

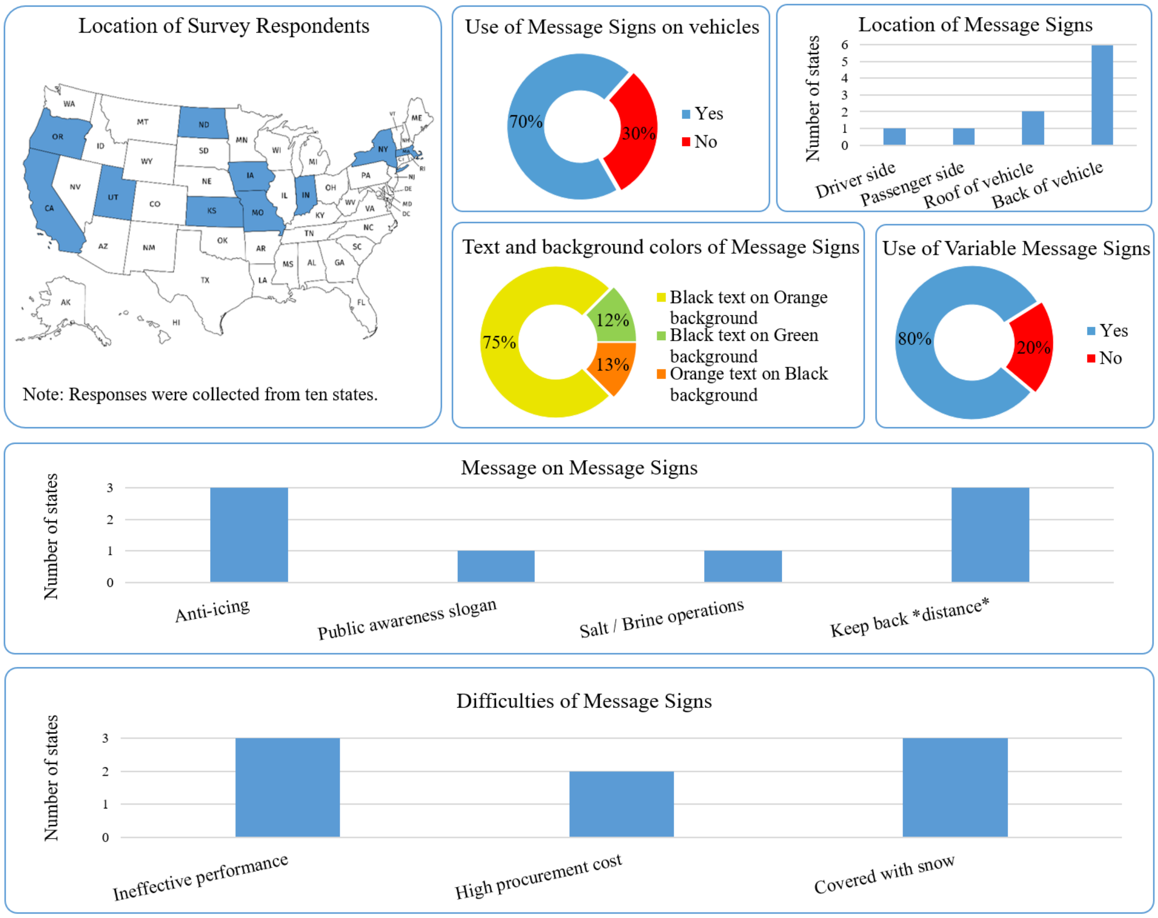


Figure 3-19 Survey results of ten states other than Texas on the evaluation of message signs of winter operations vehicles

3-2-6 Retroreflective Markings

The responses from 14 TxDOT districts were collected in this section of the survey and summarized in Figure 3-20. All 14 districts use chevron stripes on the back of their winter operations vehicles, and 13 of them use red and white stripes. The TxDOT districts reported difficulties due to short life spans of the markings as their primary challenge.

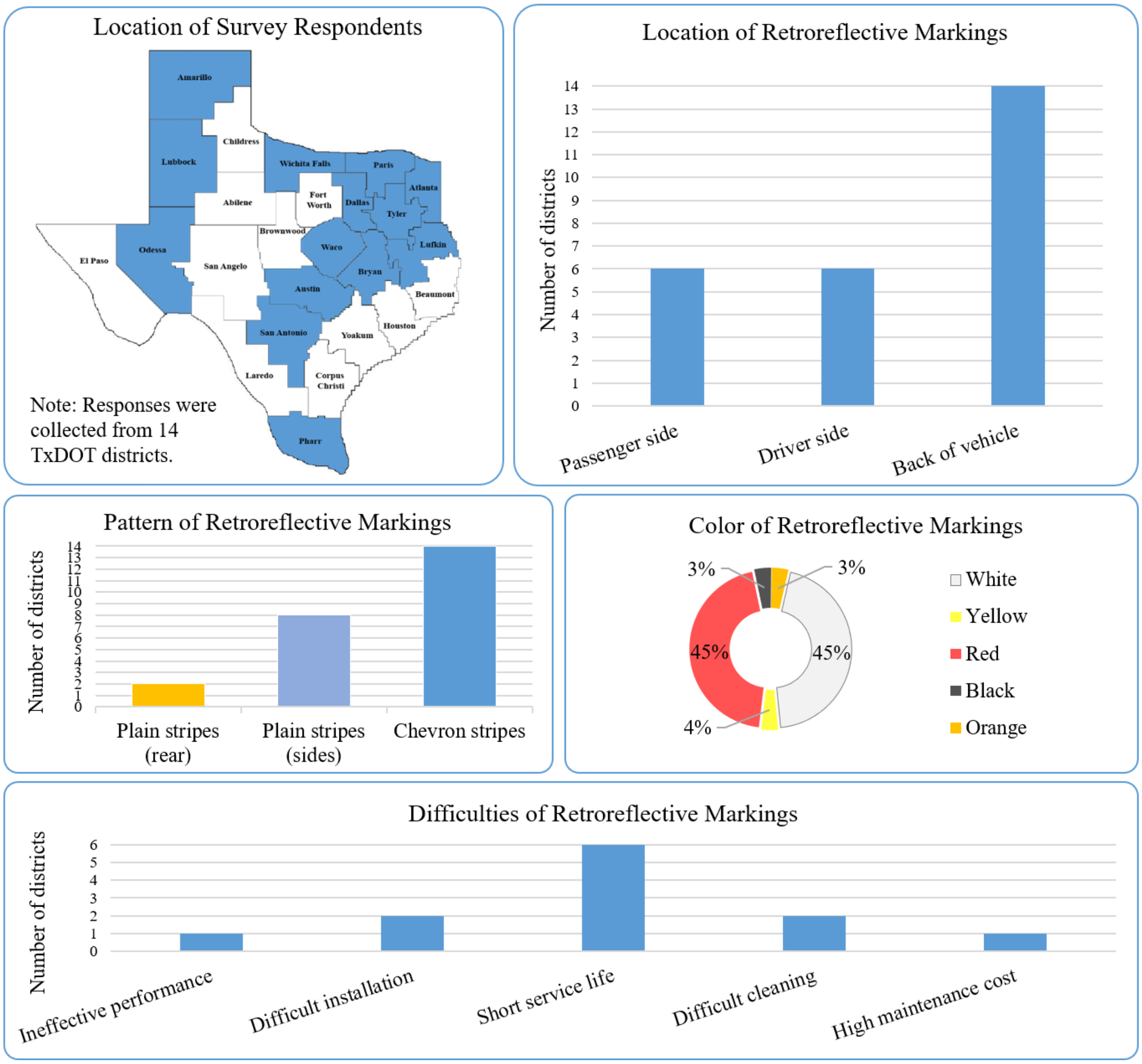


Figure 3-20 Survey results of 14 TxDOT districts on the evaluation of retroreflective markings on winter operations vehicles

Responses from the ten states other than Texas on the use of retroreflective markings are summarized in Figure 3-21. Respondents in four states indicated that they do not use these markings. In the other five states, yellow is a common color used for the markings, along with red and white. The reported difficulties of retroreflective markings were short service life, as well as snow sticking to their surfaces.

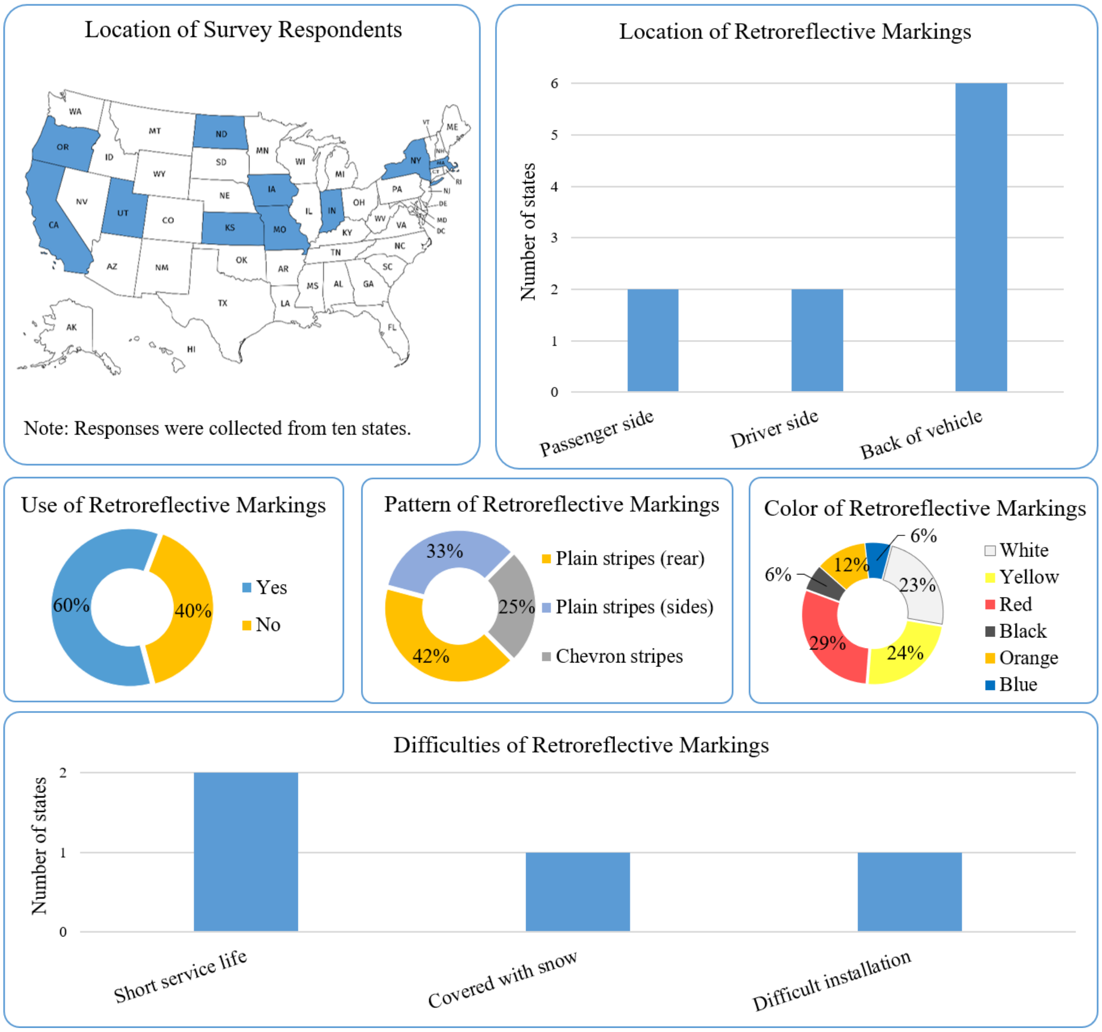


Figure 3-21 Survey results of ten states other than TxDOT on the evaluation of retroreflective markings on winter operations vehicles

3-2-7 Rear Airfoils

Responses from 14 TxDOT districts were collected in this section of the survey and summarized in Figure 3-22. Only one district (Amarillo) reported using rear airfoils as a safety application in winter weather operations. The airfoils were reported to be ineffective during snow conditions.

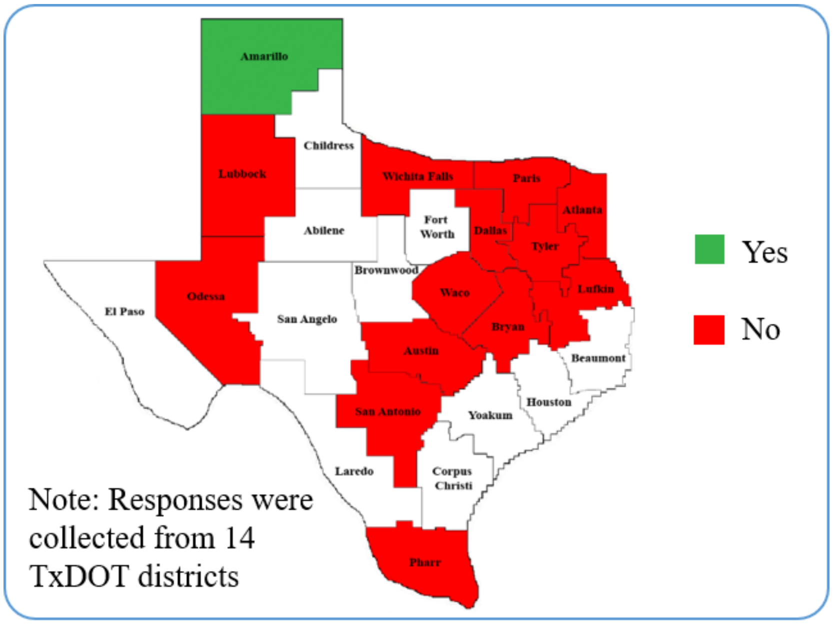
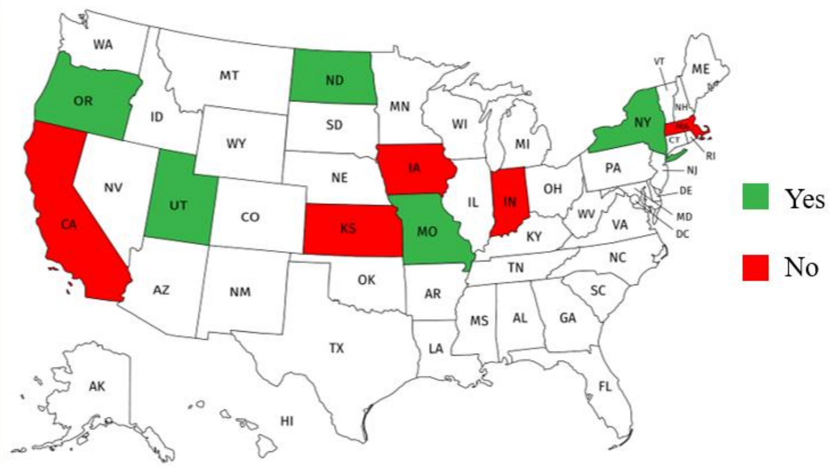


Figure 3-22 Use of rear airfoils in TxDOT districts

Responses from ten states other than Texas were also collected in this section of the survey (Figure 3-23). Throughout the U.S., Missouri, New York and North Dakota respondents use rear airfoils. In all responses the airfoils were reported to be ineffective during snow conditions, especially when the snowfall is heavy and wet. The New York respondent reported high maintenance cost for the airfoils as well. The respondent from Utah reported that the airfoils could be damaged while loading materials on the operations vehicles.



Note: Responses were collected from ten states.

Figure 3-23 Use of rear airfoils in ten states other than Texas

3-2-8 Wind Deflectors

Responses from 12 TxDOT districts and ten states other than Texas were collected in this section of the survey. Survey results on the use of wind deflectors show that none of the Texas districts use wind deflectors as safety applications in winter weather operations. In the ten states other than Texas, only the Missouri and Utah respondents reported wind deflector usage. However, the Missouri respondent discontinued wind deflector usage due to inefficient performance.

3-2-9 Smart Snowplow Systems

Responses from 13 TxDOT districts were collected in this section of the survey and summarized in Figure 3-24. Nine out of the 13 TxDOT districts use Global Positioning System (GPS) for their winter weather operations. GPS is the only smart snowplow system used by winter operations vehicles in Texas.

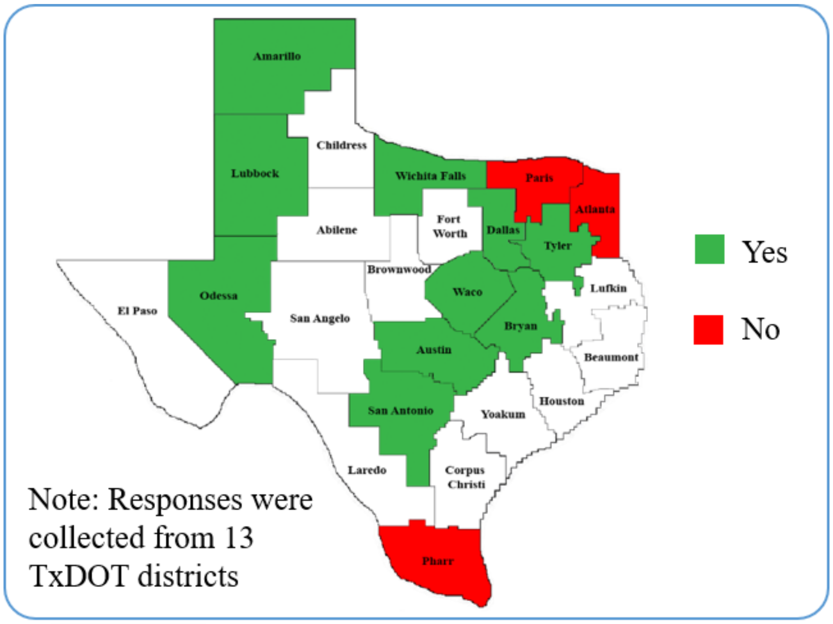


Figure 3-24 Use of smart snowplow systems (GPS) in TxDOT districts

Responses from the ten states other than Texas on the evaluation of smart snowplow systems are illustrated in Figure 3-25. Different states use a multitude of smart systems to aid in winter operations. Of the ten states surveyed, seven reported using a Road Weather Information System (RWIS) to assist in winter weather operations. The Iowa respondent reported compressed air usage to keep operations vehicle lights clear of snow. In Indiana, computer-controlled brine spreaders are used. In New York, environmental sensors automatically activate digital message signs to warn commuters about hazardous road conditions. The Utah respondent reported having a few snowplows with weather stations installed on them.

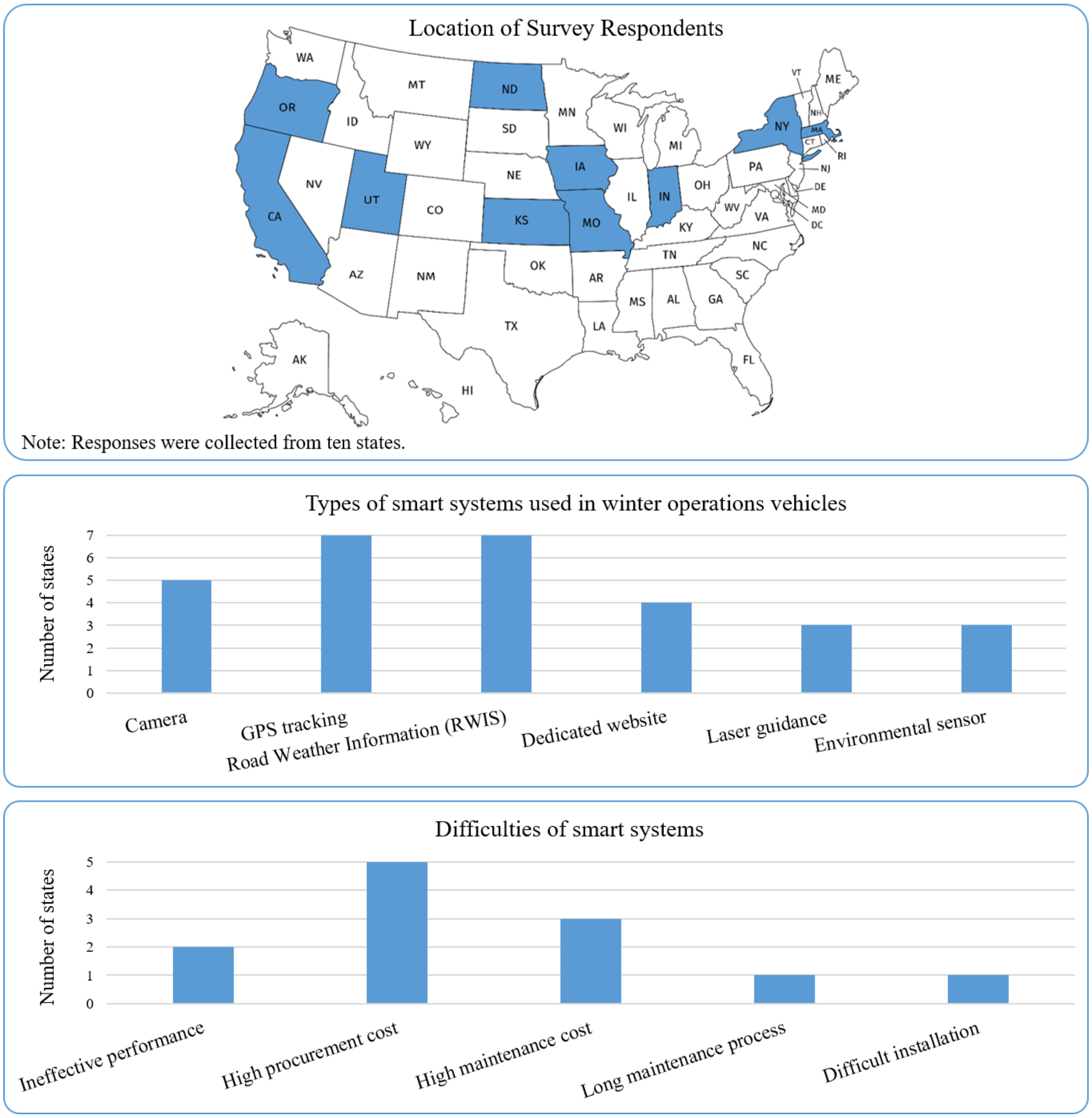


Figure 3-25 Survey results of the ten states other than Texas on the evaluation of smart system on winter operations vehicles

3-2-10 Follow-up

The follow-up section asks for the individuals who are willing to participate in the follow-up interviews and want to share more insight about their experience in the field of safety applications in winter weather operations. Figure 4-26 shows the distribution of responses in Texas to this question.

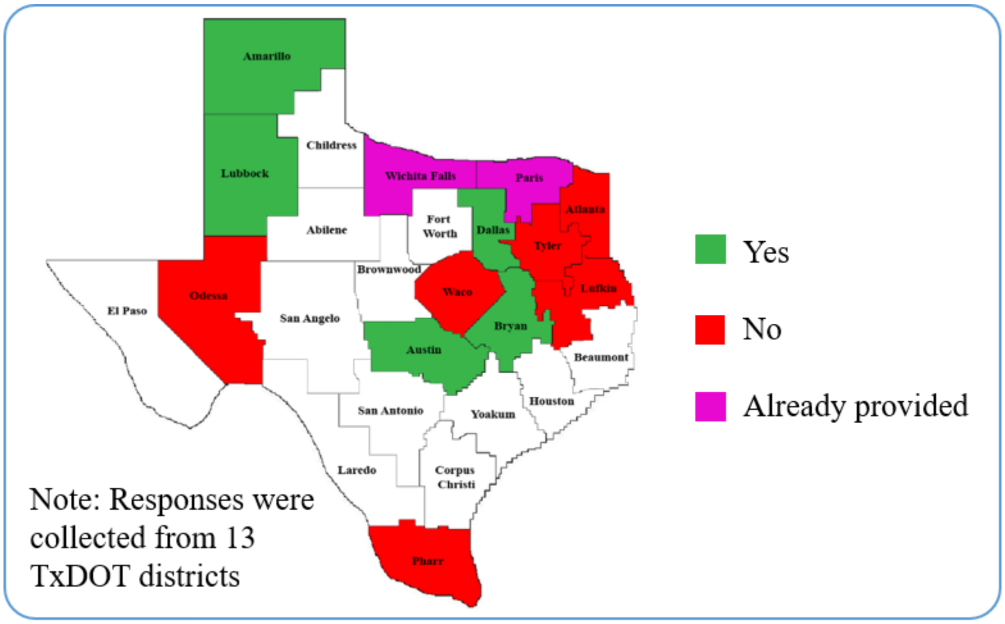


Figure 3-26 Districts who are willing to participate in follow-up interviews

Figure 3-27 shows the distribution of responses in the ten states other than Texas to this question.

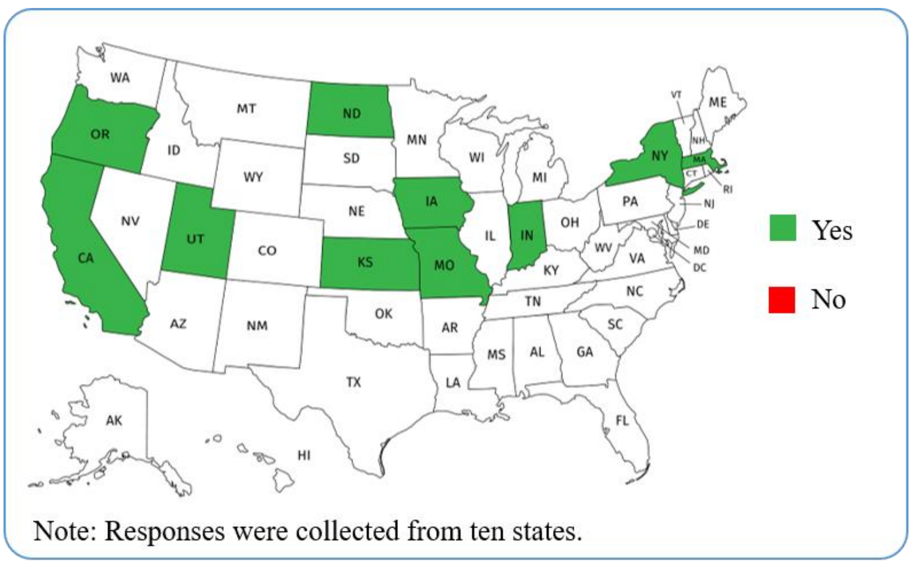


Figure 3-27 States who are willing to participate in follow-up interviews

CHAPTER 4
INTERVIEWS AND CASE STUDIES

The research team conducted follow-up interviews on different TxDOT districts to identify recommendations for best winter weather operations methods. These interviews were aimed to identify interviewee's best practices and lessons learned from real projects. Selection of interviewees, instructions for interviews, interview questions, interview results, selection of case studies and case study results have been presented in this chapter.

4-1 SELECTION OF INTERVIEWEES

The research team considered the following criteria to choose interviewees:

- Selecting individuals that are willing to participate in the follow-up interviews.
- Selecting interviewees from different TxDOT districts with the most adverse winter conditions.
- Selecting respondents that provided the most detailed information in their survey responses; and
- Selecting individuals from TxDOT districts experienced with innovative and advanced winter weather operations methods.

Based on these criteria, the research team conducted interviews with six TxDOT districts: Amarillo, Childress, Dallas, Lubbock, Paris and Wichita Falls.

4-2 INSTRUCTIONS FOR CONDUCTING FOLLOW-UP INTERVIEWS

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

1. Reviewing contact information.
2. Reviewing survey responses and asking whether interviewees would like to further explain their responses;
3. Acquiring more detailed information on the utilized winter operations methods; and
4. Obtaining recommendations to improve the safety of existing winter operations methods.

4-3 INTERVIEW QUESTIONS

The research team conducted interviews focusing on (but not limited to) the following questions:

- What are the best safety methods currently used by your district for winter weather operations (e.g., snow plowing and de-icing)?
- What are the innovative techniques you use to increase the visibility of winter operations vehicles?
- What are the most advanced technologies you use to provide safety to winter operations vehicles?
- What are the current challenges for providing safety to winter weather operations vehicles?
- What are your recommendations regarding upgrades of existing safety methods for winter weather operations?

4-4 INTERVIEW RESULTS

In total, the research team conducted interviews with respondents from six TxDOT districts: Amarillo, Childress, Dallas, Lubbock, Paris and Wichita Falls. These interviews were aimed to identify interviewee's current practices, prevailing problems, and suggested improvements for winter weather operations. Summaries of the interviews are presented in this section.

4-4-1 Interviewee Number 1 (Maintenance Supervisor, Wichita Falls District, TxDOT)

Current practices in winter operations

- Retroreflective markings (fluorescent) are installed as chevron stripe patterns.
- Roads are pretreated with brine before winter weather events. Brine is carried by 1000-gallon trucks, which are calibrated to supply 50 gallons of brine per lane per mile. Average speed of these trucks are about 55 miles per hour.
- Truck mounted attenuators (TMA) are attached to snowplows when enough employees and equipment are available.
- Snowplows are monitored using "Network fleet", a software that shows location of the plows via GPS. The service is provided by Verizon. The locations are updated periodically in about 10 to 30 minutes.

Prevailing problems during winter operations

- Snowplows frequently get hit from the rear due to low visibility in snow. Most of the collisions occur in the passing lanes.
- Not enough employees and equipment are available to cover all winter operations during severe snowstorms. As a result, single person units have to be deployed, which makes the operation very risky.
- V-boxes mounted on snowplows obstruct the visibility of strobe lights (located on top of the driver) from the rear.
- No drive control plans are implemented during winter operations (e.g. no traffic signals, traffic cones or flagman) to instruct commuters about plows ahead.
- No means of informing the public (such as Dynamic Message Signs (DMS), radio broadcast, etc.) about location of ongoing winter operations.

Suggested improvements for winter operations

- Find methods to reduce snow adhering to surfaces of snowplow.
- Eliminate necessity for single person operations.
- Install retroreflective chevron stripes to the V-boxes mounted on snowplows.

4-4-2 Interviewee Number 2 (Maintenance Supervisor, Paris District, TxDOT)

Current practices in winter operations

- The district currently has 6 V-box trucks (5 with snowplowing equipment) and 2 brine trucks.
- Each truck is accompanied by a shadow vehicle during operations.
- Winter operations vehicles have red & white or red & yellow chevron striped retroreflective markings.
- The vehicles have message signs with black text over yellow background.
- Dry pre-treatment is used before snowstorm.
- District office uses Dynamic Message Signs (DMS) to communicate with commuters.
- After a major winter weather event, four crews are dispatched to US75 roadway, and one crew is dispatched on US82 roadway.

- Winter operations vehicles are tracked online through "Network fleet".

Prevailing problems during winter operations

- Using dry pre-treatment generates dust which adheres to lights and retroreflective markings of winter operations vehicles, making them less visible.
- Sometimes icing occurs on bridges but not on roadways. It increases risk of collision because traffic flows at regular speed over the bridges, unlike reduced speeds if the road was icy as well.
- Commuters try to speed up and overtake winter operations vehicles, increasing the risk of collision.
- Providing shadow vehicles increases risk of collisions because two vehicles are operating instead of one.
- Providing shadow vehicles also increase the risk for shadow vehicle drivers, because the shadow vehicles are smaller than other winter operations vehicles and will take greater damage if hit by traffic.
- LED lights are less visible during daytime.
- Winter operations vehicles need to be cleaned after each operation, which is time consuming and labor intensive.
- "Network fleet" does not provide video or audio communication between vehicle operators and district office. As a result, verbal communications are done through radio or cellphone.

Suggested improvements for winter operations

- Wet pre-treatment can reduce dust adhering to lights and retroreflective markings.
- Cameras on winter operations vehicles will enable district office and the public to observe road conditions in real time.
- Lights can be mounted high above the vehicles to avoid snow/dirt accumulation, resulting in better visibility.
- Dynamic Message Signs (DMS) can be used to warn commuters about icing on bridges even when they are far away from them. DMS ensures effective broadcasting of warning messages.

4-4-3 Interviewee Number 3 (District Maintenance Engineer & Maintenance supervisor, Dallas District, TxDOT)

Current practices in winter operations

- The district has amber-blue colored warning lights installed on front and back of the winter operations vehicles.
- The operations vehicles have red & white chevron striped retroreflective markings.
- The vehicles have message signs with black text over orange background.
- Brine treatment is used before snowstorms.
- Truck mounted attenuators (TMAs) are used to reduce damage caused by rear end collisions on winter operations vehicles.

Prevailing problems during winter operations

- Although bright warning lights are helpful in identifying winter operations vehicles during daytime, the lights can cause "light-gazing" amongst commuters during nighttime. "Light-gazing" leads to unsafe driving and increases possibility of rear end collisions.
- During the most adverse winter weather conditions, it becomes essential for maintenance officials to work in 12-hour shifts. They are required to be present 1 additional hour before and after their individual shifts. Along with that, most officials commute from home during the adverse winter conditions. As a result, each winter maintenance officer has to work more than 14-hour work shifts every day.
- Dallas office does not have a dry shed for loading brine and/or salt on to winter operations vehicles. Current process of loading involves using ladders to unload brine/salt bags directly into the trucks, or unloading the bags onto a pavement surface and then loading the trucks.

Suggested improvements for winter operations

- Warning lights could have options to be turned on and off by the operator.
- District offices could have an arrangement for maintenance personnel to be able to shower and rest during the most adverse winter weather conditions. Arrangement could be made using empty shipping containers to include an air-conditioned resting area, a showering facility with hot and cold water along with a storage area for fresh towels and essential

toiletries. The arrangement is to be located in a relatively quieter place in the office, away from the operations rooms.

- District maintenance offices could have a dry shed to ensure efficient loading of salt and/or brine on to winter operations vehicles.
- Road surface and ambient air monitoring components could be connected to smart systems to obtain current road and weather conditions at various parts of the district. During snowstorms, icing conditions may vary between bridge and roadway surfaces. Incorrect weather forecasts often result in maintenance crews being sent to locations requiring less/no immediate maintenance instead of locations which need immediate maintenance. Smart systems providing real time environmental data to the district office will ensure effective utilization of maintenance crew in reduced amount of time.

4-4-4 Interviewee Number 4 (Director of Operations, Lubbock District, TxDOT)

Current practices in winter operations

- Brine is used as pre-treatment. Brine is also used to treat black ice on road surfaces.
- District has three-sided barns for storing anti-icing treatment like salt and brine.

Prevailing problems during winter operations

- Most of the treatment heads attached to the back of winter operations vehicles were designed for dry salt (solid crystals), not brine (liquid solution). As a result, during any major snowstorm event there is a deficit of winter operations vehicles capable of brine treatment.
- Some environmental sensors were installed throughout the district, especially for anti-icing solutions. However, they were not very effective and have not been maintained for a long time.
- The district office was constructed between 1950 and 1970. Winter operations vehicles and equipment were smaller back then compared to the latest vehicles. As a result, much of the facilities like dry sheds and loading areas are too small compared to modern needs.

Suggested improvements for winter operations

- Winter operations vehicles could have cameras attached to them which will transmit images in real time. It will enable the district office to monitor road conditions effectively.
- Existing environmental sensors could be integrated with Road Weather Information System (RWIS). The system and its components should be easy to maintain.
- Vehicle operators could have the option to dim the intensity of warning lights.
- More treatment heads capable of brine treatment will increase the effectivity of winter operations and decrease time taken to treat road surfaces before and after snowstorms.

4-4-5 Interviewee Number 5 (Maintenance Supervisor, Childress District, TxDOT)

Current practices in winter operations

- Brine is used as anti-icing treatment.
- Warning lights are amber and blue colored LED lights. They are installed as light bars on roof of vehicles (both front and back). The pattern of lighting is "flashing pattern". The warning lights have options to be turned on and off by the operator.
- Message signs instruct commuters to stay back a distance of 250 feet. The signs are installed on back of the operations vehicles.
- Retroreflective markings are red and white in color. The markings are in chevron stripe pattern and installed on back of the vehicles.

Prevailing problems during winter operations

- Brine is corrosive to winter operations vehicles and equipment as well as to road surfaces. Additional time and maintenance crew are required to clean the equipment properly after each operation.

Suggested improvements for winter operations

- Smart systems providing information like road surface temperature, ambient temperature and wind speed in real time could help district office utilize winter operations resources effectively.
- District offices of large districts (e.g. Dallas and Fort Worth) could have an arrangement for maintenance personnel to be able to shower and rest during the most adverse winter

weather conditions. Smaller districts like Childress require such arrangements when other districts provide additional maintenance crew for support in adverse winter weather conditions.

4-4-6 Interviewee Number 6 (District Maintenance Administrator & Special Jobs Coordinator, Amarillo District, TxDOT)

Current practices in winter operations

- Brine is used as anti-icing treatment.
- Message signs are not used on back of winter operations vehicles due to insufficient space (especially on V-boxes).
- Arrow boards (3 feet by 4 inches in dimension) are used on back of V-boxes to inform commuters about the presence of the winter operations vehicles.
- Rear airfoils are used in some winter operations vehicles. They are effective as long as the snowfall is not heavy.
- Warning lights have the options to be switched on and off by the operator.
- During winter weather operations, employees work in 16 hour shifts every day.
- Portable salt sheds are built every year. They are used to make brine solutions for the winter operations vehicles.

Prevailing problems during winter operations

- During heavy snow conditions the winter operations vehicles gets covered in snow and turns white in color, especially on the back of the vehicles. The snow makes the vehicles inconspicuous to other drivers.
- Warning lights also get covered by snow, reducing their visibility during winter operations. Warning lights placed near the bottom of winter operations vehicles are affected the most.
- Winter operations vehicles like V-boxes need to be loaded and unloaded with anti-icing treatments periodically. As a result, they do not have space on the back to install large message signs which would be visible from 250 feet away.
- During severe snowstorms, other districts provide additional winter operations vehicles and equipment for support. However, inconsistent appearance of vehicles and equipment of different districts lead to inefficiencies in collaborated winter operations.

Suggested improvements for winter operations

- Warning lights could be placed on top of the vehicles to reduce getting covered by snow.
- Heated lens could be used with LED lights to prevent buildup of snow on the lights.
- Using smart system, to provide road surface temperatures in different locations throughout the district, will allow maintenance supervisors to deploy maintenance crew effectively to required locations.
- Winter operations vehicles and equipment should be consistent in appearance for efficient collaborative operations when maintenance crews from different districts work together.

4-5 SELECTION OF CASE STUDIES

After conducting follow-up interviews, the interviewees were asked to provide detailed information for best practices of safety applications in winter weather operations that could be presented as case studies.

4-6 CASE STUDY RESULTS

The research team investigated four case studies from TxDOT districts: Amarillo, Dallas, Paris and Wichita Falls. The cases have been presented in the following sections.

4-6-1 Increased Vehicle Visibility using Retroreflective Markings

This method is used to make winter operations vehicles more conspicuous in adverse weather conditions.

Location

In Wichita Falls, the primary concern of winter maintenance operators is getting hit from behind by commuters. The concern gets worse during severe snow conditions.

Procedure

To increase the conspicuity of winter operations vehicles, the vehicles are installed with retroreflective markings. Chevron striped markings proved to be more beneficial compared to plain striped markings. The markings are red and white in color. Illustration is provided in Figure 4-1. Truck Mounted Attenuators (TMA) are provided when sufficient personnel and equipment are available. During a collision the attenuators absorb the impact, protecting the operator of the winter operations vehicle. A picture of TMA in folded position is provided in Figure 4-2.

Figure 4-1 Chevron striped retroreflective markings on winter operations vehicle in Wichita Falls District

Figure 4-2 Truck mounted attenuator (TMA) mounted behind a winter operations vehicle in Wichita Falls District

4-6-2 Increased Traffic Awareness using Message Signs and Shadow Vehicles

This method is used to warn commuters about the operational hazards of winter operations vehicles.

Location

Dallas and Paris Districts use message signs and shadow vehicles on/with their winter operations vehicles.

Procedure

Message signs of Dallas and Paris Districts have black texts on yellow background. Figures 4-3 and 4-4 shows message signs used by Dallas and Paris Districts respectively. Dallas District provides shadow vehicles when enough equipment and personnel are available. However, Paris District provides a shadow vehicle for all the district's winter weather operations. In hilly areas of Paris District, when the snowplows work downhill, a shadow vehicle is positioned on top of the hill so that travelers can be aware of the plows beforehand. A picture of shadow vehicle is provided in Figure 4-5. Along with these methods, the employees of Paris District work 13 hour shifts per day during winter, with shifts overlapping by one hour. This ensures there is no loss of time during handing over of equipment from employees of the previous shift, ensuring constant presence of winter operations vehicles on the roads of Paris District.

Figure 4-3 Message sign on back of winter operations vehicle in Dallas District

Figure 4-4 Message sign on back of winter operations vehicle in Paris District

Figure 4-5 Shadow vehicle of Paris District

4-6-3 De-icing using brine solution and reducing collision damages by using Truck Mounted Attenuators (TMA)

These methods are used to treat road surfaces (anti-icing treatment) pragmatically as well as reduce damages caused by rear end collisions of commuters with winter operations vehicles.

Location

Dallas District uses brine solution and TMAs with their winter operations vehicles.

Procedure

Dallas District uses brine solution (liquid) as an anti-icing treatment for its road surfaces. Previously, they used dry salt (solid) as an anti-icing treatment. The dry treatment caused "fogging" and buildup of ice crystals on the salt distributors attached to the rear of winter maintenance vehicles. Truck operators had to stop periodically and come out of their vehicles to clean the ice crystals manually to ensure effective distribution of the treatment. This problem has been solved successfully by using brine solution as an anti-icing treatment. Brine solution does not cause "fogging". Also, slower winter operations vehicles in Dallas District cause commuters to approach closer than 250 feet of the vehicles, despite the warning on message signs. As a result, chances of rear end collision increases, especially during adverse winter conditions. TMAs provide an impact absorbing solution to reduce the severity of rear end collisions.

4-6-4 Using Arrow Boards and reducing collision damages by using Truck Mounted Attenuators (TMA)

These methods are used to inform commuters about the presence of the winter operations vehicles as well as ensure reduced damages due to rear end collisions of commuters with winter operations vehicles.

Location

Amarillo District uses arrow boards and TMAs with their winter operations vehicles.

Procedure

Arrow boards are placed at the back of winter operations vehicles to inform commuters about the presence of the vehicles (Figure 4-6). Insufficient space at the back the vehicles (especially V-boxes) prevent the use of large message signs. Arrow boards are used as an alternative for message signs. To increase conspicuity of operations vehicles during heavy snow, pickup trucks in Amarillo have large, backward facing, flashing amber colored lights on top of regular amber-blue warning lights (Figure 4-7). Despite utilizing these methods, slow moving winter operations vehicles may become white and inconspicuous when covered in snow. As a result, chances of rear end collision increases. TMAs provide an impact absorbing solution to reduce the severity of rear end collisions (Figure 4-8).

Figure 4-6 Front (left) and back (right) of winter operations vehicle in Amarillo District

Figure 4-7 Front (left) and back (right) of a pickup truck used for winter operations in Amarillo District

Figure 4-8 Front (left) and back (right) of winter operations vehicle attached to a TMA

CHAPTER 5
RECOMMENDATIONS AND CONCLUSION

5-1 CRITICAL ANALYSIS

The data collected from the literature review, survey questionnaire, interviews, and case studies have been analyzed in this chapter. Through extensive literature review, a detailed understanding was obtained of methods used to increase the visibility of snowplows in Texas and in states other than Texas. By conducting two surveys (one for all TxDOT districts and another for all states other than Texas) responses were collected from 15 TxDOT districts and 10 states other than Texas. The responses from Texas were from the Abilene, Amarillo, Atlanta, Austin, Bryan, Dallas, Lubbock, Lufkin, Odessa, Paris, Pharr, San Antonio, Tyler, Waco and Wichita Falls districts. Respondents from the states of California, Indiana, Iowa, Kansas, Massachusetts, Missouri, New York, North Dakota, Oregon and Utah also responded to the survey. After evaluating the survey responses the best safety practices in winter weather operations were identified. The survey was followed by interviews with respondents from the Amarillo, Childress, Dallas, Lubbock, Paris and Wichita Falls districts, as well as case studies on the Amarillo, Dallas, Paris and Wichita Falls districts. These interviews and case studies aimed to identify the interviewees' best safety practices and lessons learned from real winter weather operations.

5-2 RECOMMENDATION OF BEST PRACTICES

After evaluation of safety practices in winter weather operations, the most effective methods were identified. They are as follows:

- The authors recommend that winter operations vehicles have a consistent appearance (for lighting, message signs, markings, etc.) in all TxDOT districts to make the vehicles more visible and recognizable to the general public. The practice of consistent appearance has been adopted in other states with advanced winter operations such as Iowa and Missouri.

- The authors recommend that warning lights be "amber and blue colored" LED lights. The pattern of lighting is recommended to be a "flashing pattern". Examples of the recommended warning lights have been shown in Figure 5-1.

- The authors recommend that all warning lights have options to be dimmed and turned on/off by the operator.

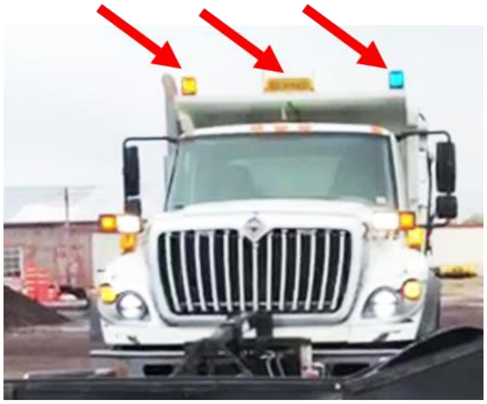



Figure 5-1 Recommended amber and blue color warning lights on top of winter operations vehicle (Amarillo District)

- The authors recommend the use of warning lights with heated lens in districts that frequently experience heavy snowfall during winter. An example of the recommended heated lens for winter operations vehicles is shown in Figure 5-2.


Figure 5-2 Recommended heated lens used with warning lights (Kansas)

- The authors recommend that message signs have "black text over orange background". It is recommended that the signs say "Stay back 250 feet". It is further recommended that signs be installed on the back of the operations vehicles (Figure 5-3).

Figure 5-3 Recommended message signs on the back of winter operations vehicles (Paris District (left) and Dallas District (right))

- The authors recommend the use of "arrow boards" if message signs cannot be installed on the back of winter operations vehicles (due to insufficient space on the back) (Figure 5-4).

Figure 5-4 Recommended arrow board on the back of a winter operations vehicle (Amarillo District)

- The authors recommend the use of red and white retroreflective markings in a chevron stripe pattern and be installed on the back of the winter operations vehicles. Examples of the recommended retroreflective markings from various TxDOT districts are shown in Figure 5-5.

Figure 5-5 Recommended retroreflective markings on the back of winter operations vehicles (Paris (left), Wichita Falls (middle) and Dallas (right) Districts)

- The authors recommend that a Winter Operations Management System (WOMS) be implemented to obtain the current conditions of roads and maintenance crews.
    - WOMS can acquire road surface temperatures and ambient air temperatures of different locations throughout a district to ensure quick and effective winter weather operations.
    - It is recommended that a dedicated website be set up to show real time images from the operations vehicles.
    - It is recommended that WOMS be integrated with existing TxDOT systems (if any).
    - It is recommended that WOMS and its components be easy to maintain.
- The authors recommend that each TxDOT district have a dry shed (permanent or temporary) to ensure efficient loading of salt and/or brine on to winter operations vehicles. Examples of dry sheds from states of Virginia and Massachusetts are shown in Figure 5-6.

Figure 5-6 Winter operations vehicles in dry sheds of Virginia Department of Transportation (VDOT) (left) (Herald Courier, 2019) and Norwell, Massachusetts (right) (Norwell Highway Department, 2019)

- The authors recommend that each TxDOT district office in urban areas have a plan for maintenance personnel to be able to shower and rest during the most adverse winter weather conditions.
    - Arrangements could be made using empty shipping containers to include an air-conditioned resting area, a showering facility with hot and cold water along with a storage area for fresh towels and essential toiletries.
    - The authors recommend that the arrangement be located in a relatively quieter place in the office, away from the operations rooms.
    - In the case of collaborative work of several districts during severe snowstorms, it is recommended that additional maintenance crew from other districts be housed in a hotel when enough arrangements are not available in the district office.

5-3 CONCLUSION

The recommendations for safety applications in winter weather operations have been suggested in addition to the existing standard specifications of winter operations, and does not replace them (standard specifications). The reduction in collisions of winter operations vehicles would significantly increase the safety and efficiency of winter operations in Texas. The benefits of safe and efficient winter operations go beyond reduced operation costs by enhancing safety, satisfaction of the general public, infrastructure conditions and service life and transportation system reliability. Moreover, the results of this study could reduce administrative costs, and traffic congestion.

REFERENCES

Ashuri, B., Shahandashti, M., & Tavakolan, M. (2014). *STC synthesis of best practices for determining value of research results*. Louisiana Transportation Research Center. Project no. 12-3PF.

Barbaccia, T. G. (2014). *PHOTOS: Ohio DOT's plow operators share their extreme winter weather stories.* January 31, 2014. Available at: https://www.equipmentworld.com/photos-ohio-dots-plow-operators-share-their-extreme-winter-weather-stories/

Bullough, J. D., Rea, M. S., Pysar, R. M., Nakhla, H. K., & Amsler, D. E. (2001). *Rear Lighting Configurations for Winter Maintenance Vehicles.* Illuminating Engineering Society of North America Annual Conference. Page no. 87-94.

Bullough, J., & Rea, M. S. (1997). *Simple model of forward visibility for snowplow operators through snow and fog at night*. Transportation Research Record: Journal of the Transportation Research Board. Volume no. 1585. Page no. 19-24.

Caltrans (California Department of Transportation) (2018). *Winter Driving Tips - Snow and Ice Control*. Retrieved on October 7, 2018. Available at: http://dot.ca.gov/cttravel/snow-ice.html

Caltrans (California Department of Transportation) (2017). *Winter Storm Warning In Effect For The Mountains: Here's What We Know About The Roads And Weather*. March 4, 2017. Available at: https://kymkemp.com/2017/03/04/winter-storm-waming-in-effect-for-the-mountains-heres-what-we-know-about-the-roads-and-weather/

CBC News (2017). *Dude, where's my plow? City of Windsor rolls out truck-tracking tech.* November 9, 2017. Available at: https://www.cbc.ca/news/canada/windsor/dude-where-s-my-plow-city-of-windsor-rolls-out-truck-tracking-tech-1.4395377

Cheng, Y. K., & Cheng, K. W. E. (2006). *General study for using LED to replace traditional lighting devices*. Second International Conference on Power Electronics Systems and Applications. Institute of Electrical and Electronics Engineers (IEEE). Page no. 173-177.

City of Winnipeg (2012). *Equipment Lighting and Visibility Requirements*. Retrieved from City of Winnipeg website: http://www.winnipeg.ca/finance/findata/matmgt/documents//2012/103-2012//1032012_Public_Works_Department's_Equipment_Lighting_and_Visibility_Requirements-Appendix_B.pdf

Coffey M. (2018). *Thompson Pass Smart Snowplow & Snow Blower*. Retrieved on November 13, 2018. Available at: http://www.dot.state.ak.us/iways/proj-smartsnowplow.shtml

Cook, S.J. (2016). *Connected Vehicle Winter Weather Maintenance Advanced Technologies Management for Motorist Advisories and Warnings.* TRB 2016 International Conference & Workshop on Winter Maintenance and Surface Transportation Weather, Fort Collins, Colorado. Available at : http://onlinepubs.trb.org/onlinepubs/Conferences/2016/wintermaintenance/presentation/cook.pdf

CTC & Associates LLC (2016). *Snowplow Truck Washing Practices: Synthesis Report.* Minnesota Department of Transportation. Report no. CR 16-S1.

CT Mirror (2015). *Snow plus salt equals Connecticut controversy.* February 10, 2015. Available at: https:/ /ctmi rror.org/2015/02/ 1 Of snow-plus-salt-equals-connecticut-controversy/

CTRE (Centre for Transportation Research and Education) (2006). *Improving Snowplow Design: Highway Maintenance Concept Vehicle Phase V*. Iowa State University. May 8, 2006.

Dahl, M. (2018). *Navigating Fleet Solutions.* Retrieved on November 6, 2018. Available at: http://www.landscapeonline.com/research/article-a.php?number=20039

Daily American (2017). *New plow in PennDOT fleet has an automatic ejector*. January 26, 2017. Available at: https://www.dailyamerican.com/entertainment/photos/new-plow-in-penndot-fleet-has-an-automatic-ejector/collection_37796c3a-e3d7-11e6-9b8b-57a5c3e5482f.html

Daily Reporter (2015). *Snowplow tracking apps hold cities accountable for cleanup.* January 20, 2015. Available at: https://dailyreporter.com/2015/01 /20/snowplow-tracking-apps-hold-cities-accountable-for-cleanup/

Dinc, M. (2011). "The Improvements of Snowplowing Safety and Efficiency: Computational Modeling and Experimental Verification". MSc thesis. University of Nevada, Reno.

District Snow Team (2018). *About Track Our Plows*. Retrieved on October 29, 2018. Available at: https://snow.dc.gov/page/about-track-our-plows

Dow, T. & Pearsall, M. (2014). *Using Value Analysis to Improve the Safety of Highway Maintenance.* Canadian Value Symposium. Toronto, Ontario, Canada.

Dur, O. (2007). *An Aerodynamic Approach to Improve Visibility During High Speed Snowplowing*. MSc thesis. University of Nevada, Reno.

Eichhorn, K. (2006). *Light-Emitting Diodes: Research, Manufacturing, and Applications III*. International Society for Optics and Photonics. Volume no. 6134. Page no. 613405.

Eklund, N., Rea, M., & Bullough, J. (1997). *Survey of snowplow operators about forward lighting and visibility during nighttime operations*. Transportation Research Record: Journal of the Transportation Research Board. Volume no. 1585. Page no. 25-29.

Esri (2014). *Plowing through winter*. September, 2014. Available at: http://www.esri.com/esri-news/arcwatch/0914/plowing-through-winter

FHWA (Federal Highway Administration Research and Technology) (2018). *Snow and Ice*. Retrieved on November 13, 2018. Available at: https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm

FHWA (Federal Highway Administration Research and Technology) (2001). *Safe Plowing Applying Intelligent Vehicle Technology*. Volume no. 64. Issue no. 4.

Fox 17 West Michigan (2015). *New feature lets you track MDOT snowplows this winter*. November 20, 2015. Available at: https://fox17 online.com/2015/11 /20/mdot-launches-new-tracking-camera-feature-to-mi-drive/

Harmon, T., Bahar, G., & Gross, F. (2018). *Crash costs for highway safety analysis*. Federal Highway Administration (FHWA). Report no. FHWA-SA-17-071.

Henderson, O.K. (2018). *DOT's lighting experiment reduced snowplow accidents. January 24, 2018*. Available at: https://www.radioiowa.com/2018/01/24/dots-lighting-experiment-reduced-collisions-with-snow-plows/

Herald Courier (2019). *Here Comes Snow Again. Region braces for second major snowstorm of season.* January 29, 2019. Available at: https://www.heraldcourier.com/news/region-braces-for-second-major-snowstorm-of-season/article _ c4dff019-af70-5349-aac6-a23ba2d67 e37 .html

Howell, B. K., Pigman, J. G., & Agent, K. R. (2015). *Work Vehicle Warning Lights: Color Options and Effectiveness*. Kentucky Transportation Center Research Report. Report no. KTC-15-06/SPR15-57-7-1F.

Jin, H., Jin, S., Chen, L., Cen, S., & Yuan, K. (2015). *Research on the lighting performance of LED street lights with different color temperatures*. IEEE Photonics Journal, Volume no. 7. Issue no. 6. Page no. 1-9.

Kamyab, A., McDonald, T., & Storm, B. (2002). *Synthesis of best practice for increasing protection and visibility of highway maintenance vehicles.* Proceedings of Mid-Continent Transportation Research Symposium, Ames, Iowa. August, 2003.

KDOT (Kansas Department of Transportation) (2017). Managing Snow and Ice. Available at: https://www.ksdot.org/PDF_Files/SnowandIceEfforts.pdf

KIWAradio (2014). *Iowa DOT Is Ready For Winter Storms; See Current Conditions From Snow Plow Cam.* November 10, 2014. Available at: http://kiwaradio.com/local-news/iowa-dot-is-ready-for-winter-storms-see-current-conditions-from-snow-plow-cam/

Kurniawan, B. A., Nakashima, Y., Takamatsu, M., & Kidoh, Y. (2007). *Visual perception of color LED light in dense fog*. Journal of Light & Visual Environment. Volume no. 31. Issue no. 3. Page no. 152-154.

Lake News (2012). *Crews begin pre-treating roads in anticipation of winter weather*. February 3, 2012. Available at: https://www.thelakenews.com/articles/crews-begin-pre-treating-roads-in-anticipation-of-winter-weather/

Laserline (2018). *GL3000PMC Wing-Tow Plow Guidance Laser.* U.S. Patent No. 7,966,753 & 8,205,360. Retrieved on November 2, 2018. Available at: https://www.laserlinemfg.com/index.php/products/wing-plow-guidance-laser/

McCullouch, B. and Stevens, B. (2008). *Investigation of The Effective Use of Warning Lights on Indiana Department of Transportation (InDOT) Vehicles and Equipment.* Report no. FHWA/IN/JTRP-2009/3.

MI Drive (2018). *MI drive Michigan.gov*. Retrieved on October 29, 2018. Available at: https://mdotjboss.state.mi.us/MiDrive/map

Minot News (2017). *Tracking Minot Snowplows, Garbage Trucks.* January 11, 2017. Available at: https://www.myndnow.com/news/minot-news/tracking-minot-snow-plows-garbage-trucks/639372689

MnDOT (Minnesota Department of Transportation) research (2018). *New System Underway to Determine Road Recovery Time During Snow Events.* November 5, 2018. Available at: https://mntransportationresearch.org/2018/11/05/new-system-in-works-to-determine-road-recovery-time-during-snow-events/

MnDOT (Minnesota Department of Transportation) (2013). *Impact of Work Zone Warning Light Configurations on Driver Behavior*. Office of Maintenance. Minnesota Department of

Transportation. November, 2013. Available at: https://www.dot.state.mn.us/maintenance/files/warninglightsstudyreport.pdf

Muthumani, A., Fay, L., & Bergner, D. (2015). *Use of Equipment Lighting During Snowplow Operations*. Minnesota Department of Transportation Report. Project no. 99006/CR14-06.

MTO (Ministry of Transportation of Ontario) (2018). *Winter Highway Maintenance: Equipment, Materials and Technology*. Retrieved on October 12, 2018. Available at: http://www.mto.gov.on.ca/english/ontario-511/winter-highway-materials-technology.shtml

MTO (Ministry of Transportation of Ontario) (2015). *Re-Establishing a Brand: A New Ontario Standard for Snow Removal Equipment Visibility*. Ontario's Transportation Technology Transfer Digest. Winter 2015. Available at: http://www.mto.gov.on.ca/english/publications/pdfs/road-talk-newsletter-winter-2015.pdf

Myers, A. D., (2017). *Snowplow Accidents: Why they happen.* Retrieved on November 11, 2018. Available at: http://attorney-myers.com/2017/03/snow-plow-accidents/

NBC (National Broadcasting Company) (2017). *Penn DOT Lets You Track Snowplows in Pennsylvania*. March 14, 2017. Available at: https://www.nbcphiladelphia.com/weather/stories/511 PA-App-Tracks-Snow-Plow-Routes-Around-Philly-366297211.html

NDOT (Nevada Department of Transportation) (2008). *Winter Maintenance Improvements: Phase I.* Report No: RDT08-001.

New Jersey Herald (2012). *Sussex County records highest snowfall in NJ*. December 27, 2012. Available at: https://www.njherald.com/story/20432537/sussex-county-records-highest-snowfall-in-nj#

NHTSA (National Highway Traffic Safety Administration) (2001). *The Effectiveness of Retroreflective Tape on Heavy Trailers.* US Department of Transportation. Report no. DOT HS 809222.

Northern Virginia Daily (2015). *VDOT unveils laser-equipped snowplow*. November 17, 2015. Available at: http://www.nvdaily.com/news/local-news/2015/11/vdot-unveils-laser-equipped-snowplow/

Norwell Highway Department (2019). *Sand and Salt Available Free to Residents*. Retrieved on June 12, 2019. Available at: http://norwelldpw.com/sand-salt-for-residents

ODOT (Ohio Department of Transportation) (2018). *ODOT's New Colored Light Combinations on Snow Removal Equipment*. Retrieved on October 9, 2018. Available at: http://www.dot.state.oh.us/Services/Pages/New-Colored-Light-Combinations-on-Snow-Removal-Equipment.aspx

ODOT (Ohio Department of Transportation) (2012). *ODOT Gives Snowplows, Drivers Green Light for Winter*. Ohio DOT District 10 Newsletter. Fall 2012. Available at: http://www.dot.state.oh.us/districts/D10/newsreleases/PublishingImages/ExternalNewsletter_Fall_2012.pdf

ODOT (Ohio Department of Transportation) (2011). *Snow & Ice Practices*. March 2011.

Otas, K., Pakenas, V. J., Vaskys, A., & Vaskys, P. (2012). *Investigation of LED light attenuation in fog*. Elektronika ir Elektrotechnika. Volume no. 121. Issue no. 5. Page no. 47-52.

Owusu-Ansah, S. (2010). *Investigation of the Relationship between Vehicle Color and Safety*. Ohio Department of Higher Education. Available at: https://etd.ohiolink.edu/

Paulichuk, D. (2005). *Snowplow Rear Lighting Research Project*. Alberta Infrastructure and Transportation. Report no. ABTR/RD/RR-05/01.

Perkins, J., Mwakalonge, J., Jasek, D., Carson, J., Obeng-Boampong, K., & Pesti, G. (2011). *Research on Best Practices for Winter Weather Operations*. Texas Department of Transportation. Report no. FHWA/TX-12/0-6669.

Pittman E. (2012). *Smart Snowplows Keep the Highway to Valdez, Alaska, Clear*. Available at: http://www.govtech.com/e-government/Smart-Snowplows-Keep-the-Highway-to-Valdez-Alaska-Clear.html

PlowTrax (2018). *City of Rochester, NY*. Retrieved on October 29, 2018. Available at: http://www.cityofrochester.gov/PlowTrax/,

Province (2014). *Beet juice helps keep B.C. roads safe*. February 23, 2014. Available at: https://theprovince.com/news/local-news/farm-photo-of-the-week-feb-23-2014-beet-juice-helps-keep-b-c-roads-safe

Rain Noe (2015). *"Missouri Farm Boy"-Turned-DOT-Engineer Invents a Better Snow-Clearing Vehicle*. February 17, 2015. Available at: https://www.core77.com/posts/29754/Missouri-Farm-Boy-Turned-DOT-Engineer-Invents-a-Better-Snow-Clearing-Vehicle

Razor tracking (2018). *City of Minot Razor Tracking*. Retrieved on October 29, 2018. Available at: https://razortracking.net/?pv=lgRgtqB

Saginaw News (2012). *Saginaw County Board of Commissioners to investigate elimination of Road Commission.* February 21, 2012. Available at: https://www.mlive.com/news/saginaw/index.ssf/2012/02/saginaw _county_ board_ of_ com mis_ 15.html

Schrank, D., Eisele, B., Lomax, T., & Bak, J. (2015). 2015 urban mobility scorecard. Texas A&M Transportation Institute. Available at: https://static.tti.tamu.edu/tti.tamu.edu/documents/mobility-scorecard-2015.pdf

Shankwitz, C. & Preisen, L. (2015). *Human Centered Technology for Handling Low Visibility: Vision Enhancement and other Driver Assistive Technologies*. University of Minnesota. Available at: http://www.its.umn.edu/Research/lVfieldtest/

SNC Lavalin O&M (2018). *Road Safety Engineering Award Submission*. Retrieved on October 11, 2018. Available at: https://www.tac-atc.ca/sites/default/files/conf_papers/safety_swing_arm_to_prevent_collisions_with_snow_plows.pdf

Star tribune (2017). *Could saltwater be the solution to Minnesota's road salt problem?* April 24, 2017. Available at: http://www.startribune.com/could-brine-be-the-solution-to-minnesota-s-road-salt-problem/4197 44553/

Transportation and Infrastructure Renewal (2018). *Provincial Plowtracker*. October 22, 2018. Available at: https://novascotia.ca/tran/winter/plowtracker.asp

TxDOT (Texas Department of Transportation) (2018). *Crashes and Injuries by Date*. Available at: http://ftp.dot.state.tx.us/pub/txdot-info/trf/crash_statistics/2018/15.pdf

TxDOT (Texas Department of Transportation) (2017). *Snow and Ice Control Operations Manual*. Manual no. 2017-1.

TxDOT (Texas Department of Transportation) (2016). *Agency Strategic Plan for Fiscal Years 2017-2021*. Available at: http://ftp.dot.state.tx.us/pub/txdot-info/sla/strategic-plan-2017-2021.pdf

Ullman, G. L., & Lewis, D. (1998a). *Texas DOT Vehicle Fleet Warning Light Policy Research*. Presentations from the 12th Equipment Management Workshop. Page no. 22.

Ullman, G., Ragsdale, J., & Chaudhary, N. (1998b). Recommendations for highway construction, Maintenance, and service equipment warning lights and pavement data collection system safety. Texas Department of Transportation. Report no. TX-99/3972-S.

USA Today (2015). *Snowplows spin off scores of winter accidents*. Available at: https://www.usatoday.com/story/news/nation/2015/01/01/snowplow-accidents-iowa/21175767/

USA Today (2011). *Iowa deploys laser plows for sharper snow removal.* November 30, 2011. Available at: https://usatoday30.usatoday.com/weather/news/2008-11-30-iowa-laser-snowplows_N.htm

Vogt, T., & Miller, K. (2008). *LED Lighting for Snowplows and Related Maintenance and Construction Vehicles*. Minnesota Department of Transportation. Report no. MN/RC 2008-29.

Washington Top News (2015). *VDOT ready to battle Northern Va. Snow.* November 12, 2015. Available at: https://wtop.com/weather-news/2015/11 /vdot-ready-to-battle-northern-va-snow/

West Fargo Pioneer (2016). *Lasers give snowplow drivers an extra set of eyes.* December 13, 2016. Available at: http://www.westfargopioneer.com/news/4178861-lasers-give-snow-plow-drivers-extra-set-eyes

WITF (2019). *Travel restrictions lifted; for now.* January 20, 2019. Available at: http://www.witf.org/news/2019/01/travel-restrictions-lifted-for-now.php

Yonas, A., & Zimmerman, L. (2006). *Improving the ability of drivers to avoid collisions with snowplows in fog and snow.* The University of Minnesota. Report no. Mn/DOT 2006-29.

4WP (2018). *Headlights, Housings and Conversions*. Retrieved on November 10, 2018. Available at: https://www.4wheelparts.com/b/lighting/replacement-parts/headlights-housings-conversions/_/N-cm7kp?No=48&Nrpp=24&productSelectedTab=true

511PA (2018). *Travel Info to go*. Retrieved on October 22, 2018. Available at: https://www.511pa.com/PlowTrucks.aspx

APPENDIX A
VALUE OF SYNTHESIS OF SAFETY APPLICATIONS IN WINTER WEATHER OPERATIONS

INTRODUCTION

Table A-1 presents the summary of the value of research (VoR) estimation for Project 0-6996 based on the functional areas selected by the Texas Department of Transportation (TxDOT). In this table, the benefit areas are associated with qualitative and economic (quantitative) benefits. Qualitative benefits of transportation research are those benefits that are not directly quantifiable, such as safety (Ashuri et al., 2014). On the other hand, the quantitative benefits are those that can be quantified as savings after implementation, such as reduction in construction operations and maintenance costs (Ashuri et al., 2014). In the following sections, the qualitative and economic benefits of this research across various areas have been discussed.

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

Benefit Area	***Qual***	***Econ***	***Both***	***TxDOT***	***State***	***Both***
Reduced Operations and Maintenance Cost		×		×		
Level of Knowledge	×			×		
Safety	×					×
System Reliability	×			×		
Increase Service Life	×			×		
Management and Policy	×			×		
Reduced Administrative Costs	×			×		
Traffic and Congestion Reduction	×					×
Customer Satisfaction	×					×

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

REDUCED OPERATIONS AND MAINTENANCE COST

Cleaning and maintaining the roads in adverse weather conditions is very challenging. Despite all precautions taken by the snowplow operators, accidents may happen during winter weather operations. Low visibility during winter weather conditions is one of the main causes of winter operations vehicle crashes. During 2015 to 2018, the Iowa Department of Transportation (IOWADOT) conducted a research to see the impact of improved visibility of snowplows on the number of snowplow crashes. The research showed that almost 9 percent of snowplows were involved in crashes due to low visibility in winter weather operations at 2014. The research also showed that adding rear facing blue-white-amber lighting system to snowplows has a deterrent effect on the number of crashes and it decreased number of crashes by approximately 73 percent from 2014 to 2017. According to Clear Roads (a national research consortium for winter highway maintenance), Texas Department of Transportation has 628 state-owned plow trucks. If we assume 9 percent of those snowplows are involved in accidents (similar to IOWADOT experience), we would have at least 56 accidents per year in Texas. Assuming TxDOT can achieve almost 73 percent reduction in the number of accidents (by improving the snowplow visibility), at least 41 snowplow accidents could be prevented each year. By evaluating TxDOT distribution of crash types (Table A-2) with FHWA recommended comprehensive crash costs (Harmon and Gross, 2018), an approximate amount of saving could be calculated. It was calculated that by preventing 41 crashes involving winter operations vehicles, TxDOT could save approximately seven million dollars annually (Table A-3).

Table A-2 TxDOT distribution of type of crashes for 543,537 accidents in 2018

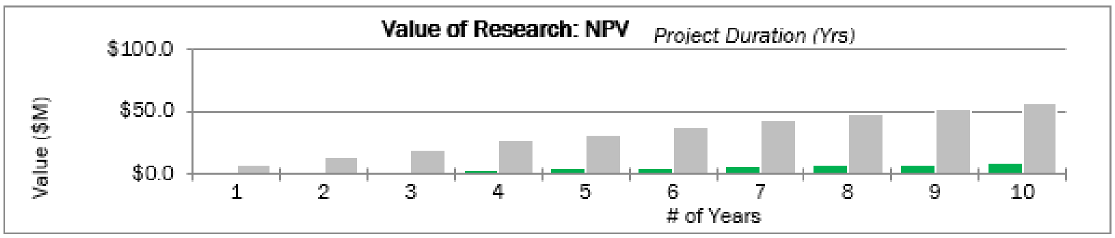
	Fatal Crashes	**Suspected Serious Crashes**	**Non-incapacitating Crashes**	**Possible Injury Crashes**	**Non-injury Crashes**
TxDOT distribution of type of crashes in 2018	0.6%	2.23%	9.96%	18.64%	64.27%

Table A-3 Projected annual savings in Texas by improving visibility and safety of winter operations vehicles

	Fatalities	**Suspected Serious Injuries**	**Non-incapacitating Injuries**	**Possible Injury**	**Non-injuries**
KABCO comprehensive crash unit cost 2016	$11,295,400	$655,000	$198,500	$125,600	$11,900
TxDOT $ saving per category	$3,100,548	$736,572	$1,106,296	$1,520,038	$977,343
Total TxDOT Saving per Year	$7,440,797				

The comprehensive crash costs used in our calculations include tangible impact (economic costs) along costs associated with physical pain, discomfort, anxiety and emotional distress resulted from accidents (Harmon et al., 2018). In a 10-year horizon, by assuming that the discount rate is 5%, the net present value of this research project (with $49,999 capital cost) will be over $61 million (Figure A-1).

	Project #	0-6996		
	Project Name:	Synthesis of Safety Applications in Winter Weather Operations		
	Agency:	UTA	**Project Budget**	$ 49,999
	Project Duration (Yrs)	1.0	**Exp. Value (per Yr)**	$ 7,440,797
	Expected Value Duration (Yrs)	10	**Discount Rate**	5%
Economic Value				
Total Savings:	$ 74,357,971		**Net Present Value (NPV):**	$ 61,758,724
Payback Period (Yrs):	0.006720		**Cost Benefit Ratio (CBR, $1 : $___):**	$ 1,235



Years	Expected Value
0	$7,390,798
1	$7,440,797
2	$7,440,797
3	$7,440,797
4	$7,440,797
5	$7,440,797
6	$7,440,797
7	$7,440,797
8	$7,440,797
9	$7,440,797
10	$7,440,797

Years	Expected Value	Expected Value	Expected Value	NPV
0	$7,390,798	$7,390,798	$7.39	$7.04
1	$7,440,797	$14,831,595	$14.83	$13.79
2	$7,440,797	$22,272,392	$22.27	$20.22
3	$7,440,797	$29,713,189	$29.71	$26.34
4	$7,440,797	$37,153,986	$37.15	$32.17
5	$7,440,797	$44,594,783	$44.59	$37.72
6	$7,440,797	$52,035,580	$52.04	$43.01
7	$7,440,797	$59,476,377	$59.48	$48.04
8	$7,440,797	$66,917,174	$66.92	$52.84
9	$7,440,797	$74,357,971	$74.36	$57.41
10	$7,440,797	$81,798,768	$81.80	$61.76

Notes:

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

Figure A-1 Value of Synthesis of Safety Applications in Winter Weather Operations

SAFETY

Adverse weather conditions have a significant impact on the safety of road operations (Perkins et al., 2011). Snowplows operate under the most inclement winter conditions, moving at slower speeds in comparison to ordinary traffic. The combined effect of low speed and low visibility cause a majority of the winter operations vehicles crashes (Myers, 2017). According to the Federal

Highway Administration (FHWA, 2018), approximately 117,000 people are injured and 1,300 are killed in vehicle crashes on snowy, slushy and icy roads annually. Assuming similar reductions in the number of crashes as IOWADOT experienced by improving visibility of winter operations vehicles, it is expected that this research is going to prevent 41 crashes in Texas annually. Details of the types of crashes and injuries (by considering TxDOT distribution of crash and injury types) have been presented in Table A-4.

Table A-4 Distribution of crash and injury types for 41 prevented crashes

	Fatal Crashes	**Fatal injuries**	**Suspected Serious Crashes**	**Suspected Serious Injuries**	**Non-incapacitating Crashes**	**Non-incapacitating Injuries**	**Possible Injury Crashes**	**Possible Injuries**	**Non-injury Crashes**	**Non-injuries**
Distribution of crash and injury types for the 41 prevented crashes	0.25	0.27	0.92	1.12	4.08	5.57	7.65	12.10	26.35	82.13

LEVEL OF KNOWLEDGE

The information on safety applications in winter weather operations methods are extensive but not concentrated. First and foremost, this research collected the latest information on winter weather operations methods from all districts of Texas, as well as from other states in USA. By synthesizing all the gathered information, this research recommended safe practices for TxDOT winter maintenance crew. This research improved knowledge for successful implementation of winter weather operations methods by providing recommendations based on gathering information from literature review and collecting experience from TxDOT personnel.

SYSTEM RELIABILITY

Based on the statistic previously presented under “Reduced Operations and Maintenance Cost”, 41 winter operations vehicle crashes can be reduced annually. It will result in fewer lane closures and increased travel time. So, implementing this research will have a significant impact on system reliability. This research project provides value by identifying and evaluating reliable winter weather operations methods. It also provides recommendations for safe winter weather operations methods. For instance, our research showed the branding of consistent colors and markings on winter operations vehicles creates an easy awareness of the vehicles to the general public, greatly increasing the system reliability.

MANAGEMENT AND POLICY

This research project provides value by synthesizing critical information in a single repository of standard, safe winter operations practices and avoiding the consequences of uninformed decisions regarding winter operations. The results of this synthesis research provide the opportunity for managers and policy makers to improve the state of practice of winter weather operations methods.

REDUCED ADMINISTRATIVE COSTS

Clearing accidents on roads and controlling subsequent damages (paying for injured employees, public and insurance) require administrative paperwork. Reducing collisions in winter weather operations result in a decrease in the costs associated with administrative tasks. This research provides value with respect to this benefit area by synthesizing and evaluating safe winter weather operations methods and by recommending methods that could prevent future collisions. This research project also creates value by providing educational materials that can be accessed by TxDOT managers and decision makers. TxDOT spent approximately $600 per employee in 2015 (TxDOT, 2016) for various training programs. This research project provides the opportunity to reduce the annual training expenditure by providing intelligible educational materials.

TRAFFIC AND CONGESTION REDUCTION

This research project identifies safe winter weather operations methods resulting in reduced congestion during snow/ice conditions. In 2015, Americans spent 6.9 billion hours in traffic and consumed 3.1 billion gallons of fuel that was equivalent to $160 billion in time and fuel loss (Schrank et al. 2015).

CUSTOMER SATISFACTION

By improving the safety of winter weather operations, we could decrease the number of accidents on roadways. Assuming similar improvements experienced by IOWADOT, the number of accidents could be decreased by almost 73 percent. By reducing the number of accidents, we can directly contribute to customer satisfaction. Having a safe and smooth traffic flow during maintenance operations will reduce delays caused by accidents and also decrease customer dissatisfaction resulted from road closure.

APPENDIX B
SURVEY QUESTIONNAIRE FOR TEXAS DISTRICTS

Survey on Synthesis of Safety Applications in Winter Weather Operations

INTRODUCTION

The University of Texas at Arlington invites you to participate in a short survey on safety applications of winter operations vehicles. This survey is an integral part of the Texas Department of Transportation (TxDOT) Research and Technology Implementation (RTI) Project #0-6996, titled: "Synthesis of Safety Applications in Winter Weather Operations." The objective of this survey is to identify current safety applications used in winter operations vehicles of TxDOT and other state DOTs. We expect this survey to take approximately 15 minutes. Your knowledge and experience are crucial to the research. TxDOT and our research team highly appreciate your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research.

If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

CONTACT INFORMATION

Please provide the following contact information.

Name	
Position	
District	
Address	
City/Town	
State	
E-mail	

GENERAL INFORMATION

1) How often do you use shadow vehicles in winter weather operations? (**Shadow vehicles** are moving trucks spaced a short distance from a moving operation, giving physical protection to workers from traffic approaching from the rear).

☐Always

☐When enough personnel are available

☐When enough equipment (vehicle) are available

☐When the snow is heavy and visibility is low

☐When operations are during night shift

☐Never

2) Please upload pictures of your winter weather operations vehicle. (If available)

Front of your **winter operations vehicle**.

Drop files of click here to upload

Back of your **winter operations vehicle**.

Drop files of click here to upload

WARNING LIGHTS

Warning lights installed on winter operations vehicles play a significant role to increase the conspicuity of the vehicles for other drivers, and increase surrounding visibility for the drivers operating the vehicles. The increased visibility of the winter operations vehicles due to the warning lights enhances the safety of winter operations. Type of warning light bulb, color, intensity, pattern, location, and size represent the most critical factors affecting the conspicuity of warning lights.

1) Please indicate all the colors your agency uses as warning light on your winter operations vehicles. (Please select all that apply)

☐All amber

☐Amber-white

☐Amber-blue

☐Amber-red

☐Amber-green

☐All blue

☐Blue-white

☐Blue-red

☐Blue-green

☐All white

☐White-red

☐White-green

☐All red

☐Red-green

☐All green

☐White-red-blue

☐Other (please specify) ☐

2) Does your district have restrictions in the use of any particular warning light color installed on your winter operations vehicles?

☐Yes

☐No

Please specify the restricted color. (Please select all that apply)

☐Amber/Yellow

☐Blue

☐Green

☐Red

☐White

3) Where are warning lights located on your winter operations vehicles? (Please select all that apply)

☐Roof of vehicle (toward front)

☐Roof of vehicle (toward rear)

☐Inside front windshield

☐Inside rear windshield

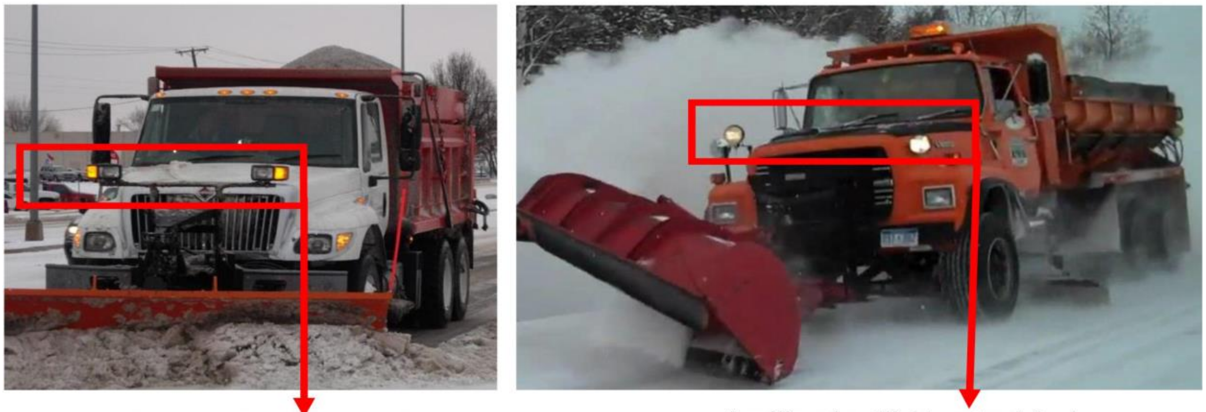
☐Front headlight assembly

☐Rear taillight assembly

☐Front plow

☐Side of vehicle (please specify the location on the side) ☐

4) Where are the auxiliary headlights mounted on your winter operations vehicles?



Auxiliary headlight on plow frame Auxiliary headlight on truck body

☐Mounted on the truck body

☐Mounted on the frame

☐Mounted on the cab hood

☐Other (please specify) ____

5) What type of **"warning light bulb"** does your agency use on the winter operations vehicles? (More than one option can be selected)

☐LED (Light-emitting diodes)

☐HID (High intensity discharge)

☐Incandescent

☐Halogen

☐Others (please specify) ____

6) What type of "warning light" does your agency use on the winter operations vehicles? (More than one option can be selected)

☐Beacon 

☐Light bar 

☐Flush mounted light (L/R) 

☐Pole mounted light 

☐Surface mounted light 

☐Others (please specify)

7) What type of "warning light pattern" does your agency use on the winter operations vehicles? (More than one option can be selected)

☐Rotating

☐Strobe

☐Flashing

☐Steady-burn

☐Others (please specify)

8) Please select all challenges of using warning lights. (Please select all that may apply)

☐High procurement cost

☐High maintenance cost

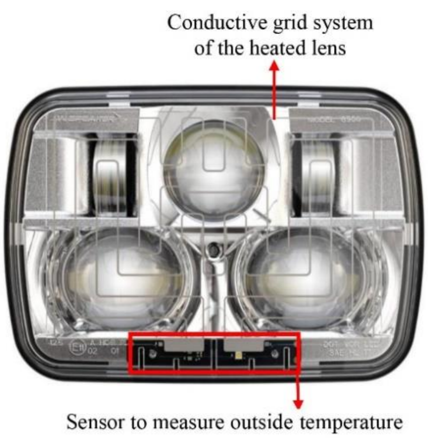
☐Difficult to install

☐Short term service life

☐Others (please specify)

HEATED LENS

Heated lens consists of a conductive grid system that warms up the lens surface to resist accumulation of snow, and a sensor to measure ambient temperature.



1) Does your agency use heated lens?

☐Yes (If yes, please specify the model of heated lens)

☐No

2) Please select all challenges of using heated lens. (Please select all that may apply)

☐It is not effective in cold snow events (around 15°F)

☐Not compatible to the existing lighting system

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

☐Long maintenance process

☐Short-term service life

☐Others (Please specify)

MESSAGE SIGNS

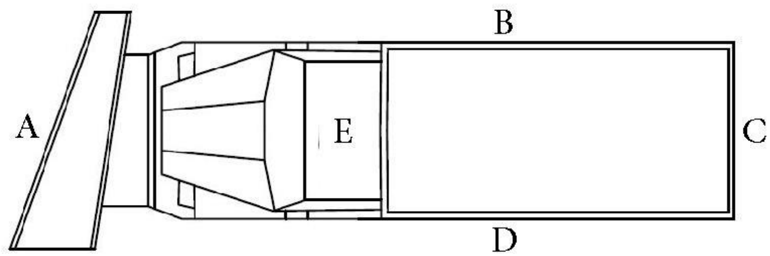
Message signs are illustrations at the back of winter operations vehicles which provides them better visibility to any vehicles coming from behind. An example is provided below.

1) Does your agency use message signs on winter operations vehicles?

☐Yes

☐No

2) Where do you install message signs on your winter operations vehicles? (Please select all that apply)



☐A (Front plow)

☐B

☐C

☐D

☐E (Roof of vehicle)

3) What messages do you have on the message signs?

☐Keep back *minimum distance* (please specify minimum distance in box below)

☐Equipment may move

☐Anti-icing

☐Other (please specify)

4) Please provide the text **color(s)** used by your agency for message signs. (Please select all that may apply)

☐Black

☐White

☐Blue

☐Red

☐Other (please specify)

5) Please provide the **background color(s)** your agency uses for message signs. (Please select all that may apply)

☐White

☐Yellow

☐Orange

☐Blue

☐Other

6) Please select all challenges of using message signs. (Please select all that may apply)

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

☐Long maintenance process

☐Short term service life

☐Other (please specify)

RETROREFLECTIVE MARKINGS

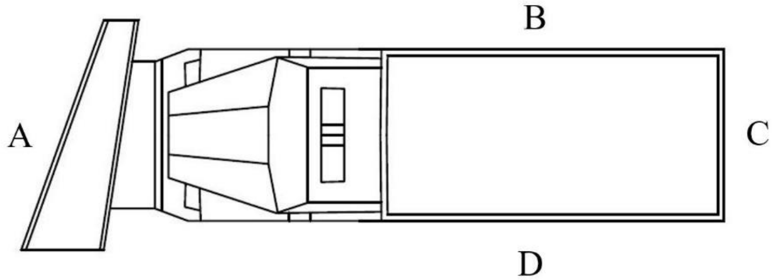
Retroreflective markings are surfaces that reflect light back to its source with the minimum amount of light scattering. Retroreflective markings are usually added on the rear and side of winter operations vehicles, which increase the visibility of the vehicles during low visibility conditions.

1) Does your agency use retroreflective markings on winter operations vehicles?

☐Yes

☐No

2) Where do you use retroreflective markings on your winter operations vehicles (including V-box spreader)? (Please select all that apply)



☐A

☐B

☐C

☐D

3) Please select the colors used in retroreflective markings on your winter operations vehicles. Examples are provided below. (Please select all that may apply)

☐Yellow

☐White

☐Blue

☐Red

☐Orange

☐Green

☐Black

☐Other (please specify)

4) Please select the patterns of retroreflective markings on your winter operations vehicles. (Please select all that may apply)

			
Plain stripes (rear)	Plain stripes (sides)	Chevron Stripes	Checkerboard Pattern

☐Plain stripes (rear)

☐Plain stripes (sides)

☐Chevron stripes

☐Checkerboard pattern

☐Other (please specify)

5) Please select all challenges of using retroreflective markings. (Please select all that may apply)

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

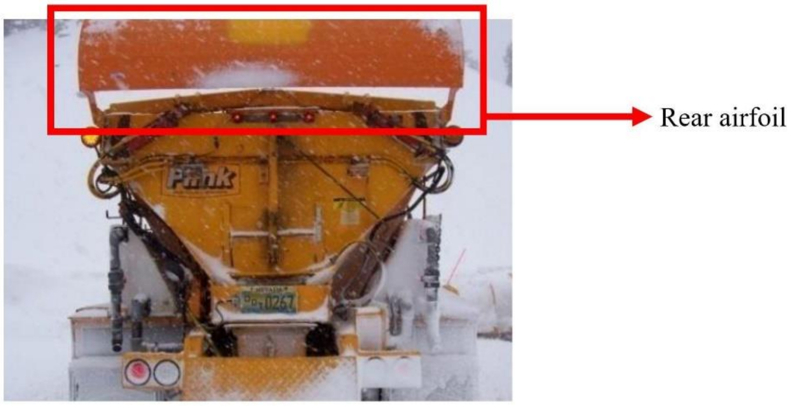
☐Long maintenance process

☐Short term service life

☐Other (please specify)

REAR AIRFOIL

Rear airfoils are metal flaps attached to the back of winter operations vehicles which direct the air flow on top of a moving vehicle down the back to prevent snow build up on the rear lighting.



1) Does your agency use rear airfoil on winter operations vehicles?

☐Yes

☐No

2) Please select all challenges of using rear airfoils.

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

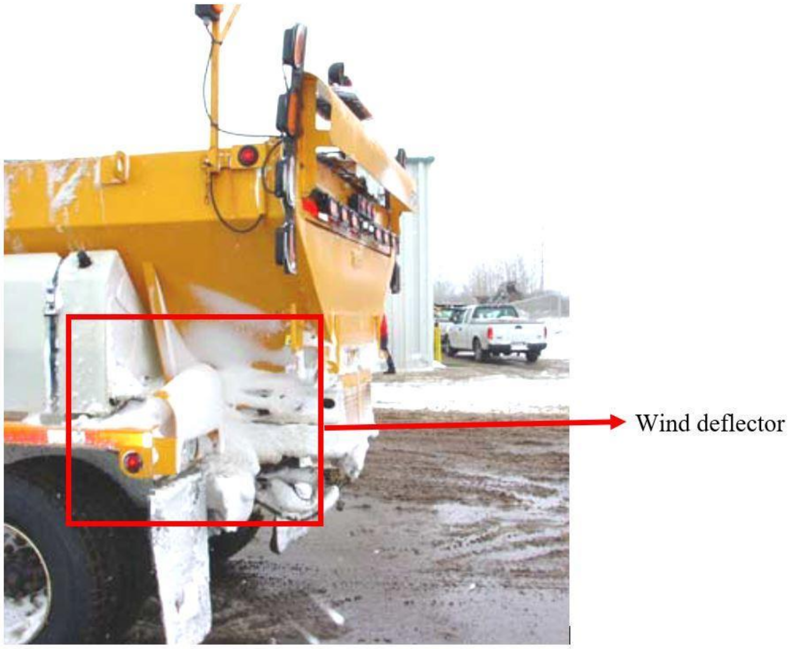
☐Long maintenance process

☐Short term service life

☐Others (please specify)

WIND DEFLECTORS

Wind deflectors are specially designed metal flaps placed over taillights of winter operations vehicles to prevent snow accumulation over the lights.



1) Does your agency use wind deflectors on winter operations vehicles?

☐Yes

☐No

2) Please select all challenges of using wind deflectors.

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

☐Long maintenance process

☐Short term service life

☐Others (please specify)

SMART SNOWPLOW SYSTEMS

Smart snowplow systems are the technologies used to provide precise information about winter operations vehicles.

1) Does your agency use Global Positioning System (GPS) to track its winter operations vehicles?

☐Yes

☐No

Follow-up

Our follow-up interview is designed to acquire practical information about the Safety Applications in Winter Weather Operations. Are you willing to share your insight in a follow-up interview?

☐Yes

☐No

Thank you for participating in this survey.

If you like to provide follow up information or if you are interested in receiving notification once the final report is completed, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or call directly at 817-271-0440.

APPENDIX C
SURVEY QUESTIONNAIRE FOR STATE DOTs OTHER THAN TXDOT

UNIVERSITY OF TEXAS ARLINGTON

Texas Department of Transportation

Survey on Synthesis of Safety Applications in Winter Weather Operations

INTRODUCTION

The University of Texas at Arlington invites you to participate in a short survey on safety applications of winter operations vehicles. This survey is an integral part of the Texas Department of Transportation (TxDOT) Research and Technology Implementation (RTI) Project #0-6996, titled: "Synthesis of Safety Applications in Winter Weather Operations." The objective of this survey is to identify current safety applications used in winter operations vehicles of TxDOT and other state DOTs. We expect this survey to take approximately 15 minutes. Your knowledge and experience are crucial to the research. TxDOT and our research team highly appreciate your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research.

If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

CONTACT INFORMATION

Please provide the following contact information.

Name	
Position	
District	
Address	
City/Town	
State	
E-mail	

GENERAL INFORMATION

1) How often do you use shadow vehicles in winter weather operations? (**Shadow vehicles** are moving trucks spaced a short distance from a moving operation, giving physical protection to workers from traffic approaching from the rear).

☐Always

☐When enough personnel are available

☐When enough equipment (vehicle) are available

☐When the snow is heavy and visibility is low

☐When operations are during night shift

☐Never

2) Please upload pictures of your winter operations vehicle. (If available)

Front of your **winter operations vehicle**.

Drop files of click here to upload

Back of your **winter operations vehicle**.

Drop files of click here to upload

WARNING LIGHTS

Warning lights installed on winter operations vehicles (snowplows) play a significant role to increase the conspicuity of the plows for other drivers and increase surrounding visibility for the snowplow drivers operating the vehicle. The increased visibility of the snowplows due to the warning lights enhances the safety of the winter operations. Type of warning light bulb, color, intensity, pattern, location, and size represent the most critical factors affecting the conspicuity of warning lights.

1) Please indicate all the colors your agency uses as warning light on your winter operations vehicles? (Please select all that apply)

☐All amber

☐Amber-white

☐Amber-blue

☐Amber-red

☐Amber-green

☐All blue

☐Blue-white

☐Blue-red

☐Blue-green

☐All white

☐White-red

☐White-green

☐All red

☐Red-green

☐All green

☐White-red-blue

☐Other (please specify) ☐

2) Does your district have restrictions in the use of any particular warning light color installed on your snowplows?

☐Yes

☐No

Please specify the restricted color. (Please select all that apply)

☐Amber/Yellow

☐Blue

☐Green

☐Red

☐White

3) Where are warning lights located on your winter operations vehicles? (Please select all that apply)

☐Roof of vehicle (toward front)

☐Roof of vehicle (toward rear)

☐Inside front windshield

☐Inside rear windshield

☐Front headlight assembly

☐Rear taillight assembly

☐Front plow

☐Side of vehicle (please specify the location on the side) ☐

4) Does your agency use warning lights on the wing plow?

Warning Light on the wing plow

☐Yes

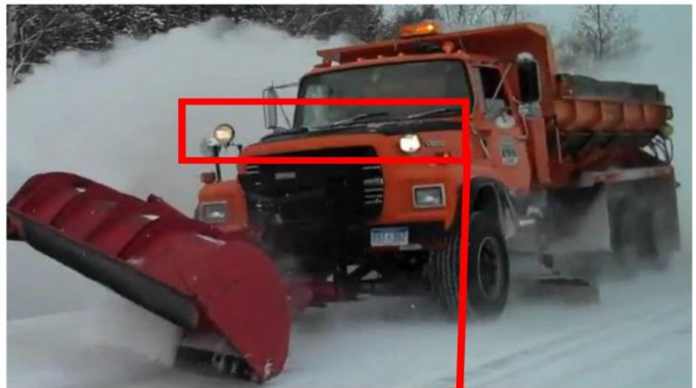
☐No

Please provide a picture of the warning light on your wing plow. (If available)

Drop files of click here to upload

5) Where are the auxiliary headlights mounted on your winter operations vehicles?

Auxiliary headlight on plow frame



Auxiliary headlight on truck body

☐Mounted on the truck body

☐Mounted on the frame

☐Mounted on the cab hood

☐Other (please specify) __________

6) What type of "warning light bulb" does your agency use on the winter operations vehicles? (More than one option can be selected)

☐LED (Light-emitting diodes)

☐HID (High intensity discharge)

☐Incandescent

☐Halogen

☐Others (please specify) __________

7) What type of "warning light" does your agency use on the winter operations vehicles? (More than one option can be selected)

☐Beacon

☐Light bar

☐Flush mounted light (L/R)

☐Pole mounted light

☐Surface mounted light

☐Others (please specify)

8) What type of "warning light pattern" does your agency use on the winter operations vehicles? (More than one option can be selected)

☐Rotating

☐Strobe

☐Flashing

☐Steady-burn

☐Others (please specify)

9) Please select all challenges of using warning lights. (Please select all that may apply)

☐High procurement cost

☐High maintenance cost

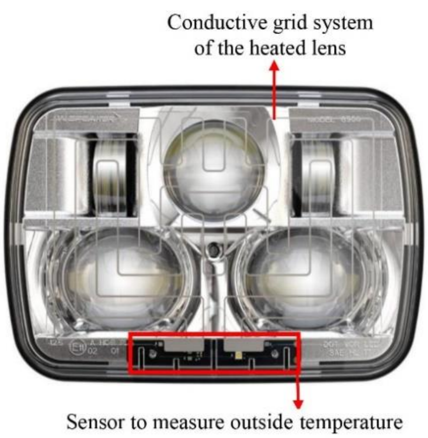
☐Difficult to install

☐Short term service life

☐Others (please specify)

HEATED LENS

Heated lens consists of a conductive grid system that warms up the lens surface to resist accumulation of snow, and a sensor to measure ambient temperature.



1) Does your agency use heated lens?

☐Yes (If yes, please specify the model of heated lens)

☐No

2) Please select all challenges of using heated lens. (Please select all that may apply)

☐It is not effective in cold snow events (around 15°F)

☐Not compatible to the existing lighting system

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

☐Long maintenance process

☐Short-term service life

☐Others (Please specify)

MESSAGE SIGNS

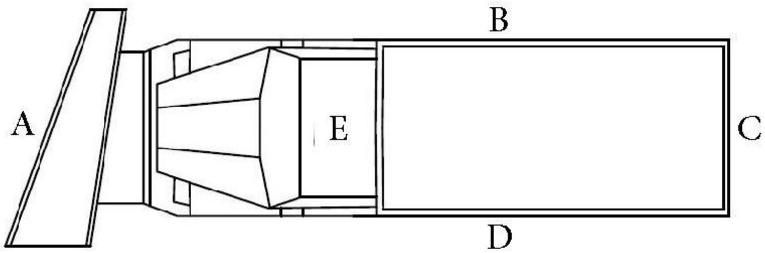
Message signs are illustrations at the back of snowplows which offer better visibility of the plows to any vehicles coming from behind. An example is provided below.

1) Does your agency use message signs on winter operations vehicles?

☐Yes

☐No

2) Where do you install message signs on your snowplows? (Please select all that apply)



☐A (Front plow)

☐B

☐C

☐D

☐E (Roof of vehicle)

3) What messages do you have on the message signs?

☐Keep back *minimum distance* (Please specify minimum distance in box below)

☐Equipment may move

☐Anti-icing

☐Other (please specify)

4) Please provide the text **color(s)** used by your agency for message signs. (Please select all that may apply)

☐Black

☐White

☐Blue

☐Red

☐Other (please specify)

5) Please provide the **background color(s)** your agency uses for message signs. (Please select all that may apply)

☐White

☐Yellow

☐Orange

☐Blue

☐Other

6) Please select all challenges of using message signs. (Please select all that may apply)

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

☐Long maintenance process

☐Short term service life

☐Other (please specify)

7) Does your agency have any changeable message signs or variable message signs? Example of a road variable message sign is shown below.

☐Yes

☐No

If yes, does your district display road warning message signs during winter weather operations?

☐Yes

☐No

RETROREFLECTIVE MARKINGS

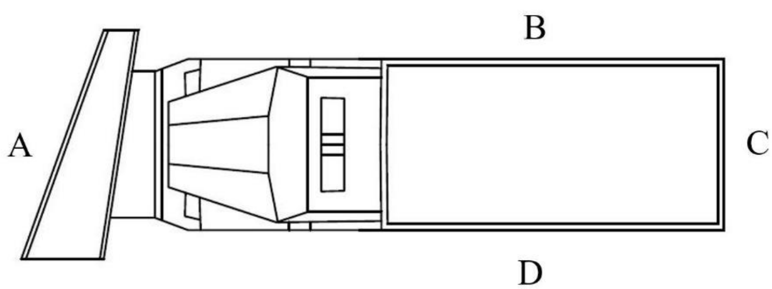
Retroreflective markings are surfaces that reflect light back to its source with the minimum amount of light scattering. Retroreflective markings are usually added on the rear and side of winter operations vehicles, which increase the visibility of the vehicles during low visibility conditions.

1) Does your agency use retroreflective markings on winter operations vehicles?

☐Yes

☐No

2) Where do you use retroreflective markings on your snowplows (including V-box spreader)? (Please select all that apply)



☐A

☐B

☐C

☐D

3) Please select the colors used in retroreflective markings on your snowplows. Examples are provided below. (Please select all that may apply)

☐Yellow

☐White

☐Blue

☐Red

☐Orange

☐Green

☐Black

☐Other (please specify)

4) Please select the patterns of retroreflective markings on your snowplows. (Please select all that may apply)

			
Plain stripes (rear)	Plain stripes (sides)	Chevron Stripes	Checkerboard Pattern

☐Plain stripes (rear)

☐Plain stripes (sides)

☐Chevron stripes

☐Checkerboard pattern

☐Other (please specify)

5) Please select all challenges of using retroreflective marking. (Please select all that may apply)

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

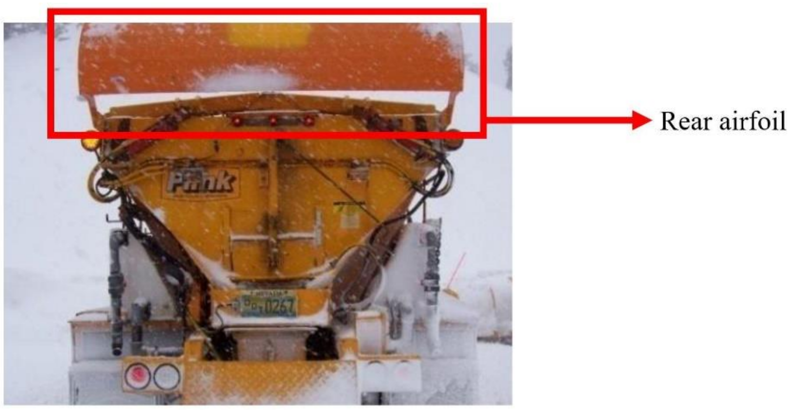
☐Long maintenance process

☐Short term service life

☐Other (please specify)

REAR AIRFOIL

Rear airfoils are metal flaps attached to the back of winter operations vehicles which direct the air flow on top of a moving vehicle down the back to prevent snow build up on the rear lighting.



1) Does your agency use rear airfoil on winter operations vehicles?

☐Yes

☐No

2) Please select all challenges of using rear airfoils.

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

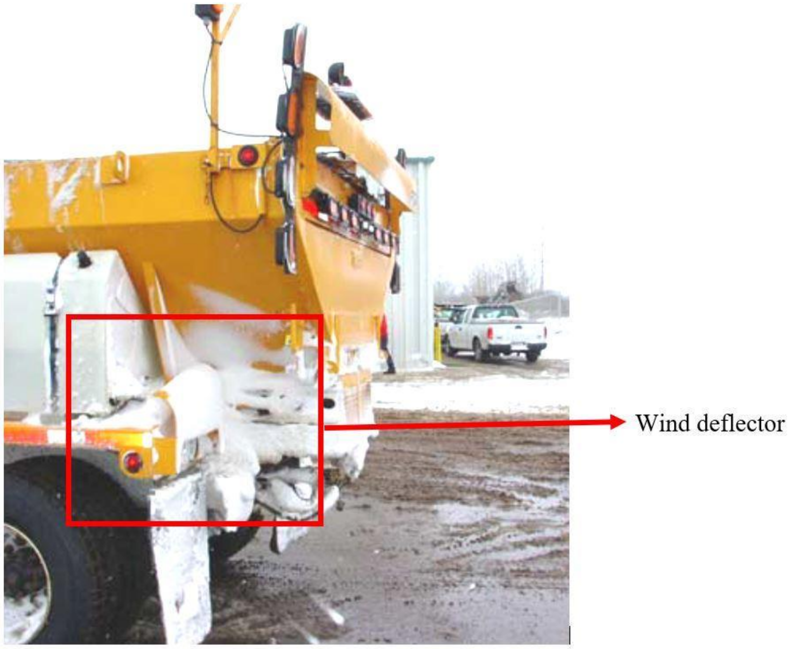
☐Long maintenance process

☐Short term service life

☐Others (please specify)

WIND DEFLECTORS

Wind deflectors are specially designed metal flaps placed over taillights of snowplows to prevent snow accumulation over the lights.



1) Does your agency use wind deflectors on winter operations vehicles?

☐Yes

☐No

2) Please select all challenges of using wind deflectors.

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

☐Long maintenance process

☐Short term service life

☐Others (please specify)

SMART SNOWPLOW SYSTEMS

Smart snowplow systems are the technologies used to provide precise information about road conditions around the snowplow trucks.

1) Please select all smart systems that are used on winter operations vehicles at your agency. (Please select all that may apply)

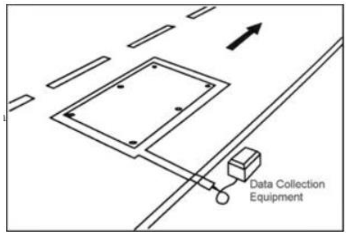
☐GPS tracking System

☐Camera

☐Real time video

☐Dedicated website

☐Road weather information system



☐Laser guide snowplow

☐None

2) Please select all challenges of using smart snowplow systems.

☐Ineffective performance

☐High procurement cost

☐Difficult installation

☐High maintenance cost

☐Long maintenance process

☐Short term service life

☐Others (please specify) ______

3) Are there any other new and innovative technologies that you may have the knowledge of or have experience of using, other than what we covered in this survey?

☐Yes (please specify) ______

☐No

Follow-up

Our follow-up interview is designed to acquire practical information about the Safety Applications in Winter Weather Operations. Are you willing to share your insight in a follow-up interview?

☐Yes

☐No

Thank you for participating in this survey.

If you like to provide follow up information or if you are interested in receiving notification once the final report is completed, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or call directly at 817-271-0440.

APPENDIX D
SURVEY INVITATION EMAIL FOR TEXAS DISTRICTS

To:

Subject: Synthesis of Safety Applications in Winter Weather Operations.

Dear Colleagues,

The University of Texas at Arlington invites you to participate in a short survey on safety applications of winter operations vehicles. This survey is an integral part of the Texas Department of Transportation (TxDOT) Research and Technology Implementation (RTI) Project #0-6996, titled: “Synthesis of Safety Applications in Winter Weather Operations.” The objective of this survey is to identify current safety applications used in winter operations vehicles of TxDOT and other state DOTs.

We expect this survey to take approximately 15 minutes. Please fill out the survey before March 15^{th}, 2019. TxDOT and our research team highly appreciates your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research.

If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

Link to the survey: https://uta.qualtrics.com/jfe/form/SV_cC8tQH5GPJi4QZf

Sincerely,

Joanne Steele, PMP, CSM

Research Project Manager

Research & Technology Implementation Division

Office: 512-416-4657

APPENDIX E
SURVEY INVITATION EMAIL FOR STATE DOTS OTHER THAN TXDOT

To:

Subject: Synthesis of Safety Applications in Winter Weather Operations.

Dear Colleagues,

The University of Texas at Arlington invites you to participate in a short survey on safety applications of winter operations vehicles. This survey is an integral part of the Texas Department of Transportation (TxDOT) Research and Technology Implementation (RTI) Project #0-6996, titled: "Synthesis of Safety Applications in Winter Weather Operations." The objective of this survey is to identify current safety applications used in winter operations vehicles of TxDOT and other state DOTs.

We expect this survey to take approximately 15 minutes. Please fill out the survey before March 15^{th}, 2019. TxDOT and our research team highly appreciates your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research.

If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

Link to the survey: https://uta.qualtrics.com/jfe/form/SV_eafoj22hJbtmL6l

Sincerely,

Mohsen Shahandashti, Ph.D., P.E., M.ASCE.
Assistant Professor
Department of Civil Engineering
The University of Texas at Arlington
Phone: 817-272-0440