EXAMINING CURRENT STATE OF PRACTICE OF ENHANCING VISIBILITY OF WINTER OPERATIONS VEHICLES

by

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ABSTRACT

EXAMINING CURRENT STATE OF PRACTICE OF ENHANCING VISIBILITY OF WINTER OPERATIONS VEHICLES

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Despite precautions taken by the operators of maintenance vehicles, insufficient visibility of winter operations vehicles cause many collisions in the United States. Numerous methods have been developed to enhance the visibility of winter operations vehicles. Although the visibility of winter operations vehicles has enhanced through these methods, the consistency in the implementation of the methods for enhancing their visibility is critical to avoid collisions. The inconsistencies in the implementation of the methods confuse the public who are traveling in winter conditions when visibility is low. The confusion leads to a delay in perception time and response time of the drivers and eventually, leads to rear-end collisions with the winter operations vehicles. Although anecdotal evidence shows the inconsistency as a barrier to the successful implementation of visibility methods, the extent of the inconsistencies is not known.

For safer winter operations, it is critical to investigate the differences, similarities, and challenges associated with the existing methods for enhancing the visibility of winter operations. The objective of this research is to investigate the differences, similarities, and challenges associated with these methods. A survey questionnaire was designed to accomplish this objective. The questionnaire was distributed among all the 50 states of the U.S. The survey questionnaire was also distributed among 25 Texas Department of Transportation (TxDOT) districts to sample the extent of such inconsistencies within a state.

In this study, the current state of knowledge and practice are captured and integrated to present the striking dissimilarities within the methods for visibility of winter operations in various states in the U.S. Even within one state (i.e., Texas), considerable differences were identified. The study also shows that some states are utilizing successful methods of visibility, like elevated warning lights and heated lenses, which are not being used by other states. On the other hand, maintenance officials consistently face challenges regarding the cleaning of their vehicles after each winter operation, which delays the time between operations and uses additional manpower. The findings of this study would help transportation agencies implement consistent methods for enhancing the visibility of winter operations vehicles.

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CHAPTER 1
RESEARCH BACKGROUND

1-1 INTRODUCTION

Winter operations vehicles operate under the most adverse conditions, generally moving at slower speeds than other traffic. Every year approximately 1,300 people are killed, and 117,000 people are injured in vehicle crashes on snowy, slushy, and icy roads (FHWA, 2018). In poor visibility conditions (like snow and fog), drivers' perception of time and response time are crucial to avoid crashes (Pietrzyk et al., 1997). The response time to unexpected objects into a driver's path is roughly 1.5 seconds, which is more than double the usual time of 0.70 seconds (Green, 2010). Seventy percent of all crashes involving winter operations vehicles are into the rear of the vehicles (Bullough et al., 2001). Winter operations vehicles must achieve a high level of visibility for the safety of the traveling public (Muthumani et al., 2015). Numerous methods have been developed to enhance the visibility of winter operations vehicles. Although the visibility of winter operations vehicles has enhanced through these methods, the consistency in the implementation of the methods for enhancing their visibility is critical to avoid collisions. The inconsistencies in the implementation of the methods confuse the public who are traveling in winter conditions when visibility is low. The confusion leads to a delay in perception time and response time of the drivers and eventually, leads to rear-end collisions with the winter operations vehicles.

The following sections provide an introduction to winter weather operations, problem statement, literature reviews, gaps in knowledge, and research objectives.

1-2 WINTER WEATHER OPERATIONS

Extreme weather conditions (i.e., snowstorm) in wintertime cause significant travel disruptions, increase delay, and traffic accidents (Chien et al., 2014). Every year, countermeasures are undertaken by the government / private organizations to reduce the disruptions, delay, and accidents. Countermeasures such as snow plowing and salt spreading are most common for making our roads safer for motorists (Chien et al., 2014). These countermeasures are carried out as winter weather operations. Vehicles such as snowplows and trucks are used to carry out the winter weather operations.

Notable research has been conducted regarding the subjects of warning lights, heated lens, message signs, retroreflective markings, rear airfoils, wind deflectors, smart snowplow systems, and laser guided snowplows. Many Departments of Transportations (DOTs) conducted research on various aspects of winter weather operations, notably the DOTs of California (Caltrans, 2018), Minnesota (MDOT, 2018), Nevada (NDOT, 2008), and Ohio (ODOT, 2012). The Federal Highway Administration Research and Technology (FHWA, 2001; FHWA, 2018) has provided manuals that offer methodologies to analyze winter operations and recommend design guidelines. Furthermore, several researchers assessed different aspects of winter weather operations or tried to introduce new techniques, such as Bullough et al. (2001), Coffey (2018), Cook (2016), Dinc (2011), Dow & Pearsall (2014), Eklund et al. (1997), Henderson (2018), Muthumani et al. (2015), Paulichuk (2005), and Shankwitz & Preisen (2015). Nevertheless, these studies did not evaluate the differences, similarities, and challenges of winter weather operations for enhancing their visibility in adverse conditions.

1-3 PROBLEM STATEMENT

Despite all precautions taken by the operators of the winter weather vehicles, accidents happen during the operations. Low visibility during winter weather conditions is one of the main causes of winter operations vehicle crashes. 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).

Therefore, a comprehensive analysis of various devices for enhancing the visibility of winter operations vehicles is necessary to identify the most appropriate devices and methods. This consideration is essential since it determines the best practices for making the winter operations vehicles visible to the traveling public in order to reduce collisions and improve the safety of roads, maintenance crew, and the traveling public. Other benefits of reduction in the number of collisions are reduced operations and maintenance cost, system reliability, increased service life, reduced administrative costs, and traffic and congestion reduction.

1-4 GAPS IN KNOWLEDGE

The previous research on the advancement of various methods for winter operations vehicles adds valuable insight into the safety of winter operations and the traveling public. However, the review of the literature shows that related studies:

1. Did not explore the differences, similarities and challenges of the methods amongst different states in the US.
2. Did not explore the differences, similarities and challenges of the methods amongst different districts of a single state in the US.

Consequently, the feedbacks from on-site maintenance personnel about existing methods of visibility is essential for the safety of the traveling public. It is necessary to recognize the best consistent practices to reduce crashes involving winter weather operations throughout the entirety of the US.

1-5 RESEARCH OBJECTIVES

The objectives of this research project were to (1) synthesize and critically evaluate existing methods and devices used for enhancing the safety of winter weather operations of the 50 states of the U.S as well as within 25 TxDOT districts; (2) recommend appropriate practices for the US maintenance crews for utilizing the best methods and devices during winter weather operations considering the conditions of different states and districts. These methods were evaluated and a comparative study was developed exploring the differences, similarities and challenges of the methods amongst different states in the US, as well as the methods amongst different districts of a single state in the US.

CHAPTER 2
RESEARCH APPROACH

2-1 INTRODUCTION

The research approach which has been followed to achieve the project objectives includes the review of the literature, survey, and interview of subject matter experts. Figure 2-1 shows the framework of the research approach.

Figure 2-1 Framework of the research approach

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 the states of the US as well as within the districts of Texas. The results of the literature analysis are presented in Chapter 3. The findings of the literature review were used to develop two surveys, one for all the states of the US and another for all TxDOT districts. The survey was distributed among maintenance professionals in the field of winter weather operations to gather information on the existing practices being used. The information obtained from the survey analysis has been presented in Chapter 4. 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 interview results in Chapter 5. The information collected from the literature review, survey questionnaires, and interviews were analyzed to present recommendations for the most effective methods for winter operations throughout the US. These recommendations have been provided in Chapter 6. Finally, Chapter 7 summarizes the conducted research and presents its contribution to the body of knowledge. It also offers recommendations for future research related to this topic.

2-2 REVIEW THE LITERATURE ON WINTER WEATHER OPERATIONS

This step focused on evaluating the existing methods and devices used for the visibility of winter weather operations. Extensive research has been done in books, articles, and reports related to this topic. Also, the state DOT websites were searched for any resource related to this topic, such as a formal approach for using a particular method of visibility.

Afterward, the methods of visibility were classified based on different techniques. This classification expedited the process of examining the consistency of the methods. Furthermore, it simplified the identification of best practices to reduce collisions related to winter weather operations.

2-3 SURVEY

Conducting surveys is one of the methods for determining the value of research in a variety of influenced areas (Ashuri et al., 2013; Shahandashti et al., 2015; Shahandashti et al., 2017). The information collected from survey responses enabled us to capture the current state of practice in winter weather operations. Survey questions were designed based on the findings of the literature review.

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.

- The most common methods and devices used for the visibility of winter operations vehicles;
- Specifications (such as placement, patterns, colors) of the existing methods;
- The ease of implementation of the existing methods;
- The difficulties regarding the existing methods;
- Their personal feedback regarding the existing methods.

2-3-1 Survey questionnaire structure

The survey questionnaire sought to capture the most important information about safety applications in winter weather operations of the various states of the US as well as the different TxDOT districts. 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 questionnaire then moved on to eight separate sections, for details regarding the common methods of winter weather operations. The sections are as follows (Shahandashti et al., 2019) –

1. Warning lights (9 questions)
2. Heated lens (2 questions)
3. Message signs (7 questions)
4. Retroreflective markings (5 questions)
5. Rear airfoil (2 questions)
6. Wind deflectors (2 questions)
7. Smart snowplow systems (3 questions)
8. Follow up (1 question)

For each method, respondents were asked to answer questions about the following topics:

- specifications regarding the use of the method

- performance of the method
- disadvantages of the method
- personal feedback regarding the method

2-3-2 Survey distribution

The surveys were distributed amongst maintenance officials with different positions throughout the US, as well as throughout all TxDOT districts. The survey questionnaire was hosted on a commercial website (http://www.qualtrics.com). An invitation email with the online link to the survey was sent to survey respondents for survey distribution. This email included a brief introduction followed by a brief instruction on how to answer survey questions.

The survey content and protocol were approved by the University of Texas at Arlington's (UTA) Institutional Review Board (IRB), which evaluated potential risks and benefits to participants, conflicts of interest, and specified the methods for collection and storage of data. Each question was provided with a set of pre-defined answers in order to make the survey quick and concise. In case any pre-defined answers were not the participant's answer of choice, there were options for the participant to provide unique details separately. Two initial drafts were circulated for review to the Texas Department of Transportation's (TxDOT) Research and Technology Implementation Division (RTI). The final questionnaire was refined based on the results of these reviews.

2-4 INTERVIEW

The research team conducted follow-up interviews on different TxDOT districts to identify recommendations for best winter weather operations methods. The interviews were focused within Texas in order to better understand the inconsistencies of winter operations methods within a single state of the US. These interviews were aimed to identify the interviewee's best practices and lessons learned from real projects. Selection of interviewees, instructions for interviews, interview questions, and interview results have been presented in this chapter. 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. The interviewees hold different positions, such as district engineer, maintenance engineer, maintenance supervisor, and transportation engineer. The selected interviewees were contacted, and over-the-phone interview sessions were scheduled at their convenient time.

2-4-1 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.

2-4-2 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?

CHAPTER 3
LITERATURE REVIEW ON SAFETY APPLICATIONS IN WINTER WEATHER OPERATIONS

3-1 INTRODUCTION

Several methods of visibility have been identified for winter operations vehicles. Figure 3-1 shows the classification of visibility methods. The following sections review the different methods in detail.

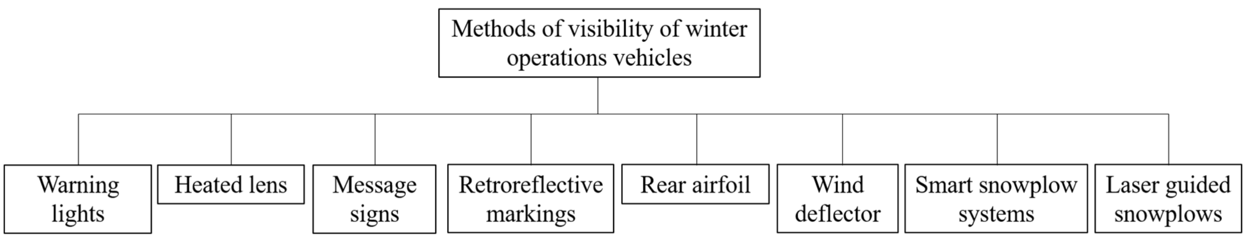

Figure 3-1 Classification of visibility methods of winter operations vehicles

3-2 WARNING LIGHTS

Warning lights installed on winter operations vehicles play a significant role in increasing 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.

3-2-1 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.

3-2-1-1 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).

3-2-1-2 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 3-2, more snow could accumulate on their surface compared to HIDs (Vogt and Miller, 2008).

Figure 3-2 Comparison between HID (left) and LED (right) Lights after Heavy Snow Conditions (Vogt and Miller, 2008).

3-2-2 Color of Warning Lights

3-2-2-1 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 3-1 illustrates the colors of lights recommended by studies in some DOTs.

Table 3-1 Light colors recommended by studies in some DOTs (Shahandashti et al., 2019)

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)

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 actual 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 motorists 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 3-3 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 snowplows involved collisions (Henderson, 2018).

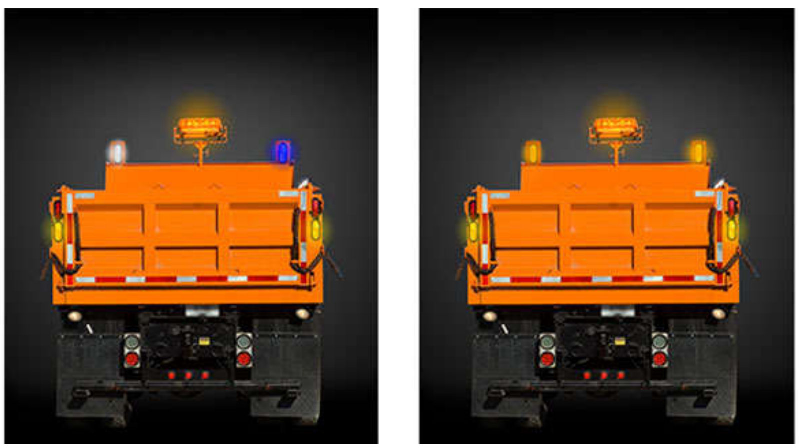

Figure 3-3 Color combination on snowplows to enhance safety: Left picture shows the latest blue lights on some snowplows and picture to the right shows enhanced amber lights on some DOT snowplows (Henderson, 2018).

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).

3-2-2-2 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 3-4 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).

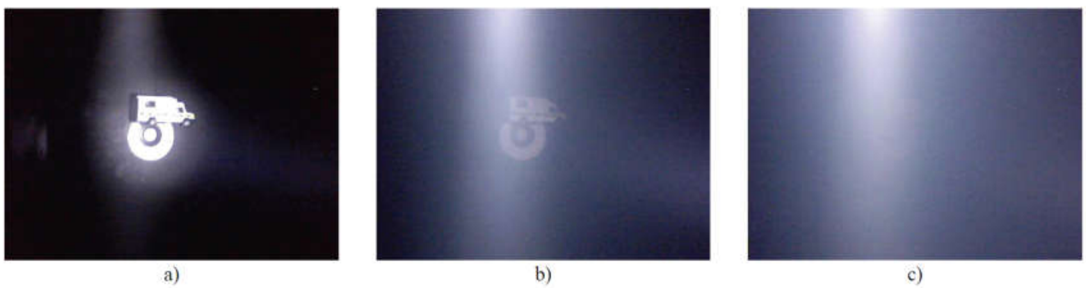

Figure 3-4 Image of the object in the fog chamber under illumination by the white LED with additional white light falling from the top for different densities of fog (a) low, (b) average, and (c) high density respectively (Otas et al., 2012).

3-2-3 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 3-2 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 3-2 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

3-2-4 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).

3-2-5 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 3-5 (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.

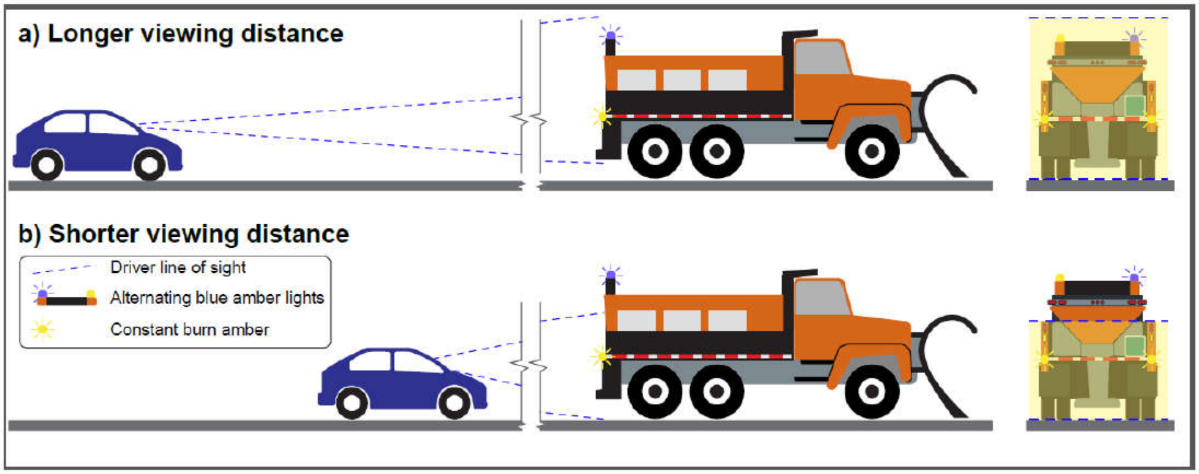

Figure 3-5 Proposed mounting locations for flashing and steady burning lights (Muthumani et al., 2015).

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.

3-2-6 Size

The size of LED warning lights must also be considered. Although McCullouch and Stevens (2008) mention 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.

3-3 HEATED LENS

A vehicle light includes several components, such as light bulb (lamp), reflector, and lens. In the 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 temperatures (Muthumani et al., 2015). Figure 3-6 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).

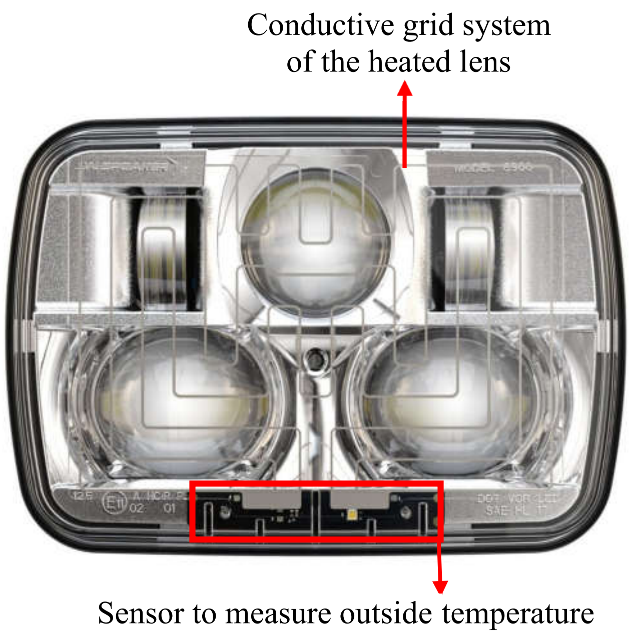

Figure 3-6 Heated lens components (4WP, 2018)

3-4 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.

In 2015, the 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 day-time 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 3-7 (MTO, 2015).

Figure 3-7 Message sign on the back of winter operations vehicles (MTO, 2015)

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 3-8 shows a message sign with yellow background used by Caltrans.

Figure 3-8 Message sign on the back of a winter weather operations vehicle in California (Caltrans, 2017)

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 3-9 (Star Tribune, 2017).

Figure 3-9 Message sign behind a winter operations vehicle in Minnesota (Star Tribune, 2017)

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 3-10 shows the safety campaign decals on the back of a snowplow.

Figure 3-10 "Ice & Snow…Take It Slow" decals on ODOT's snowplow trucks (ODOT, 2011)

Winter operations vehicles in Pennsylvania carry a message sign instructing drivers to stay 100 feet away from the vehicles, as shown in Figure 3-11 (WITF, 2019).

Figure 3-11 Message sign on the back of a winter operations vehicle in Pennsylvania (WITF, 2019)

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 3-12 (Saginaw News, 2012).

Figure 3-12 Winter operations vehicles in Saginaw County (Michigan) with message signs at the back (Saginaw News, 2012)

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 3-13.

Figure 3-13 Message sign on the back of a winter operations vehicle of Sussex County, New Jersey (New Jersey Herald, 2012)

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 3-14.

Figure 3-14 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 3-15).

Figure 3-15 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 put anti-icing message signs (Figure 3-16) on their backs during winter weather operations (Province, 2014).

Figure 3-16 "Anti-icing" message sign on the back of a winter operation vehicle of British Columbia (Province, 2014)

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 3-17.

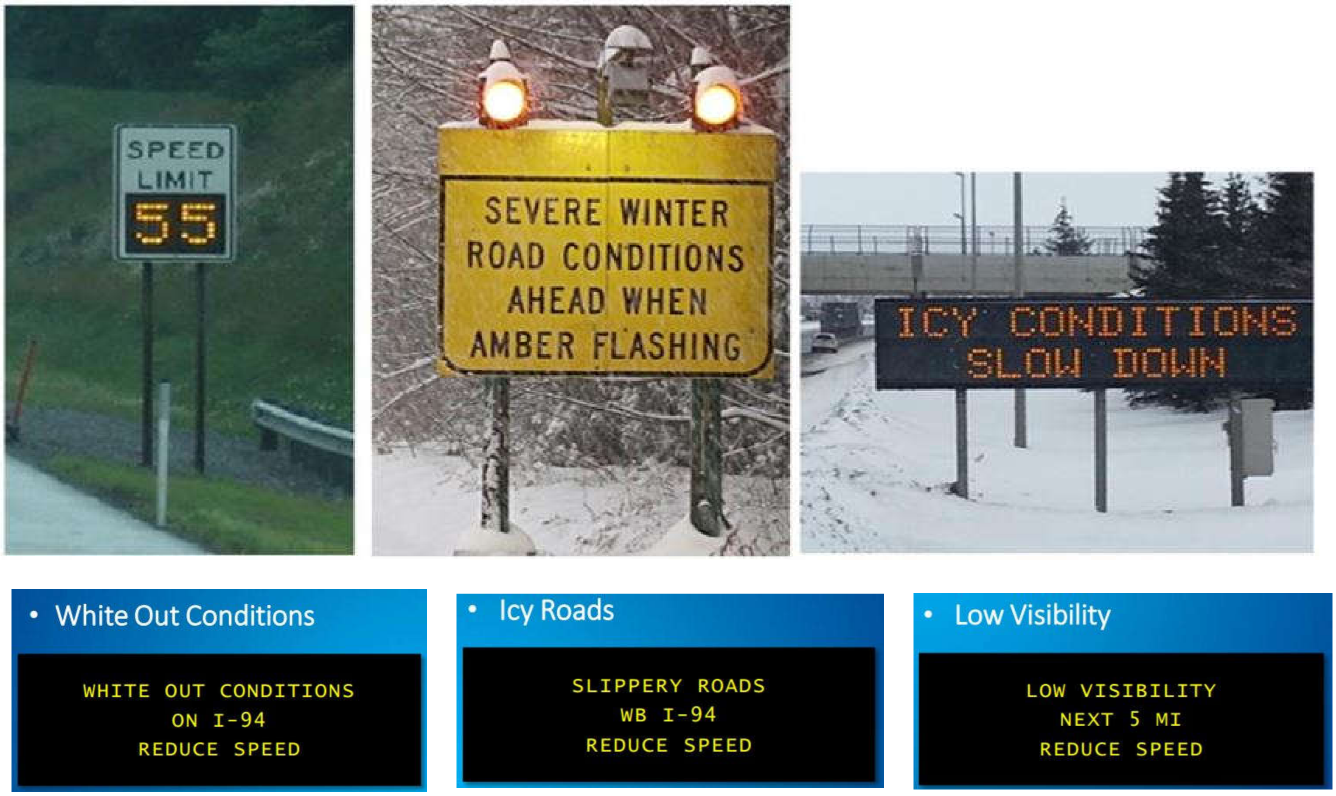

Figure 3-17 Examples of Motorist Advisory and Warnings signs in Michigan (Cook, 2016)

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 3-18).

Figure 3-18 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 3-19, on roadside message boards.

Figure 3-19 Fixed traveler message sign warning drivers of icy road conditions in Kansas (KDOT, 2017)

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 3-3 summarizes the message sign colors used in some DOTs.

Table 3-3 Message sign colors used in some DOTs (Shahandashti et al., 2019)

State DOT		Color of text	Color of background
Ministry of Transportation of Ontario (MTO)		Black	Yellow
California DOT		Black	Yellow
Michigan DOT		Black	Yellow
Minnesota DOT		Black + Red	White
Ohio DOT		Black	Orange
New Jersey DOT		Black	Orange
Pennsylvania DOT		Black	Orange
De-icing Message Signs	***MTO***	Black	Yellow
	Kansas DOT	Black	Orange
	Kentucky DOT	Black	Orange
	British Columbia Ministry of Transportation	Black	White

3-5 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.

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 3-20.

Figure 3-20 Red and white retroreflective tape fully outlining the rear tailgate of a winter operations vehicle in Ontario (Dow & Pearsall, 2014)

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 3-21.

Figure 3-21 Safety Swing Arm with retroreflective markings (SNC Lavalin O&M, 2017)

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 ten 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).

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).

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 3-22.

Figure 3-22 A winter operations vehicle of Virginia DOT with red and white retroreflective markings on the side (Washington Top News, 2015)

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 3-23.


Figure 3-23 Warning signs on the back of winter operations vehicles in Ohio (ODOT, 2018 (left); Barbaccia, 2014 (right))

The backs of winter operations vehicles in Pennsylvania have red and yellow warning signs (Daily American, 2017), illustrated in Figure 3-24.

Figure 3-24 Warning sign on the back of a new winter operations vehicle in Pennsylvania (Daily American, 2017)

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 3-25). 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 3-25 Warning sign on the back of Indiana DOT V-Box spreader (McCullouch and Stevens, 2008)

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 3-26.

Figure 3-26 Warning signs on the back of a winter operations vehicle in Connecticut (CT Mirror, 2015)

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 3-4 summarizes the retroreflective marking colors used in some DOTs

Table 3-4 Retroreflective marking colors used in some DOTs (Shahandashti et al., 2019)

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

3-6 REAR AIRFOIL

Rear airfoils or tailgate (rear) deflectors are metal flaps attached to the back of winter operations vehicles; the airfoils direct the airflow of a moving vehicle down the back to prevent snow build up on the rear lights and retroreflective markings. The diverted airflow from the top of the vehicle creates an aerodynamic shear caused by the high momentum airflow, 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 3-27.

Figure 3-27 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 3-28.

Figure 3-28 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 3-29 shows the practical version of the experiment.

Figure 3-29 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.

3-7 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 3-30 illustrates how the system is installed behind the winter operations vehicles.

Figure 3-30 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 3-31 and 3-32.

Figure 3-31 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 3-32 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.

3-8 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. Data capture technologies are being increasingly utilized as the level of understanding of smart technologies are increasing (Taneja et al., 2018). 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).

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 3-33.

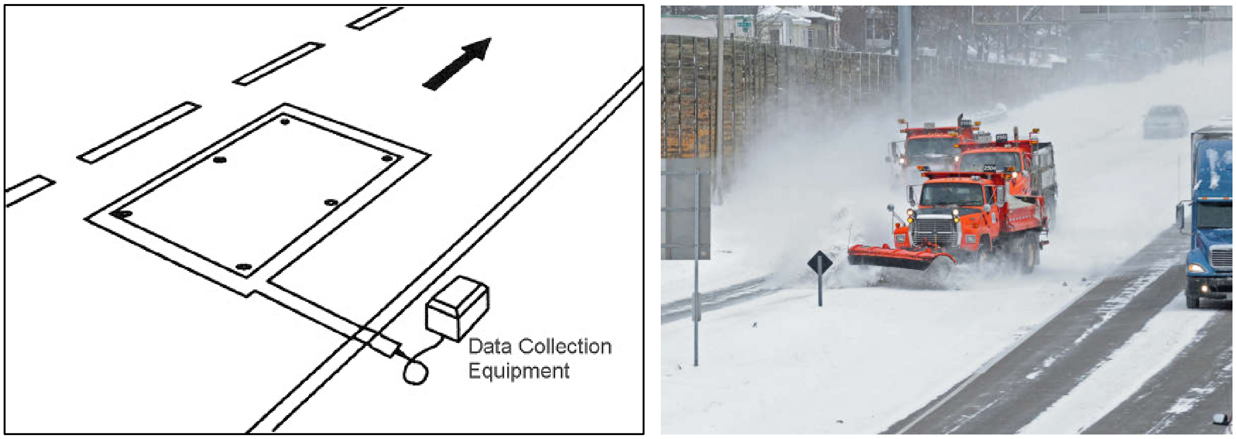

Figure 3-33 Line drawing of a rectangular closed wire loop (6 feet long and 4 feet wide) beneath road surface of Minnesota, used to collect data from the road and direct winter operations vehicles towards harder-hit roadways swiftly through the computer system (MnDOT research, 2018)

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 the 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 a 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 3-34.

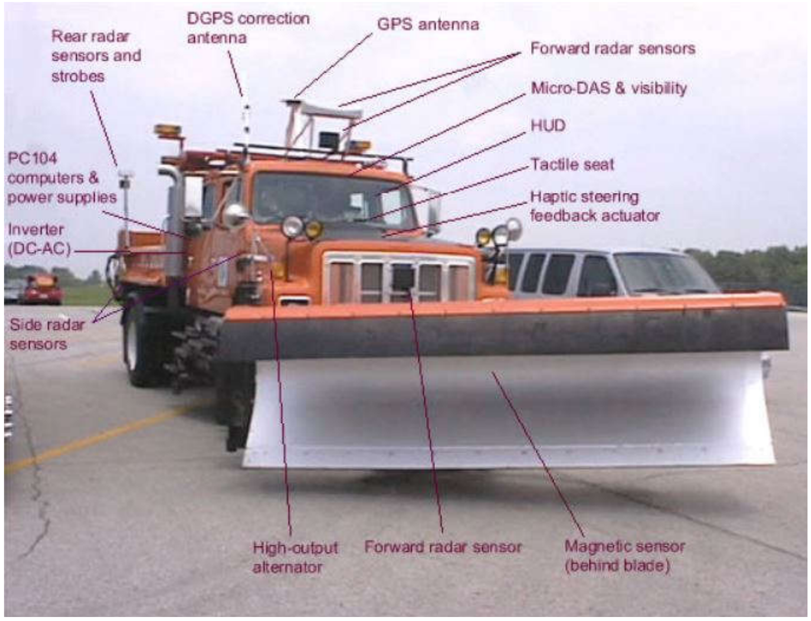

Figure 3-34 A winter operations vehicle of Minnesota DOT installed with equipment for HUD and GPS (Shankwitz & Preisen, 2015)

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), provides 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 underlaid during the 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 on 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 3-35 shows a winter operations vehicle equipped with HUD.

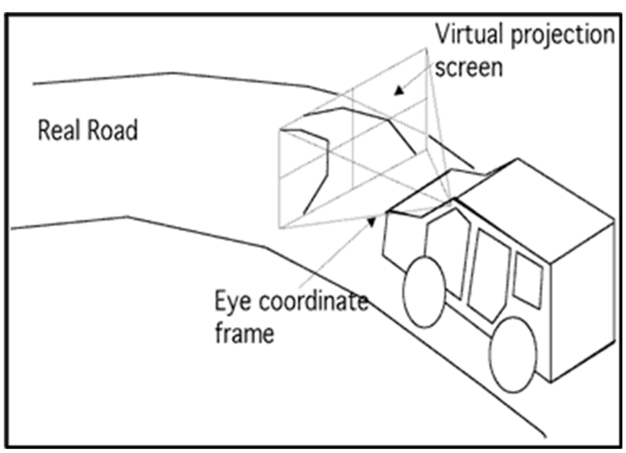

Figure 3-35 Schematic drawing of the working principle of HUD (left), and HUD installed on a winter operations vehicle of Minnesota (right) (Shankwitz & Preisen, 2015)

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 with 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.

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 3-36 shows the Plowtracker website.

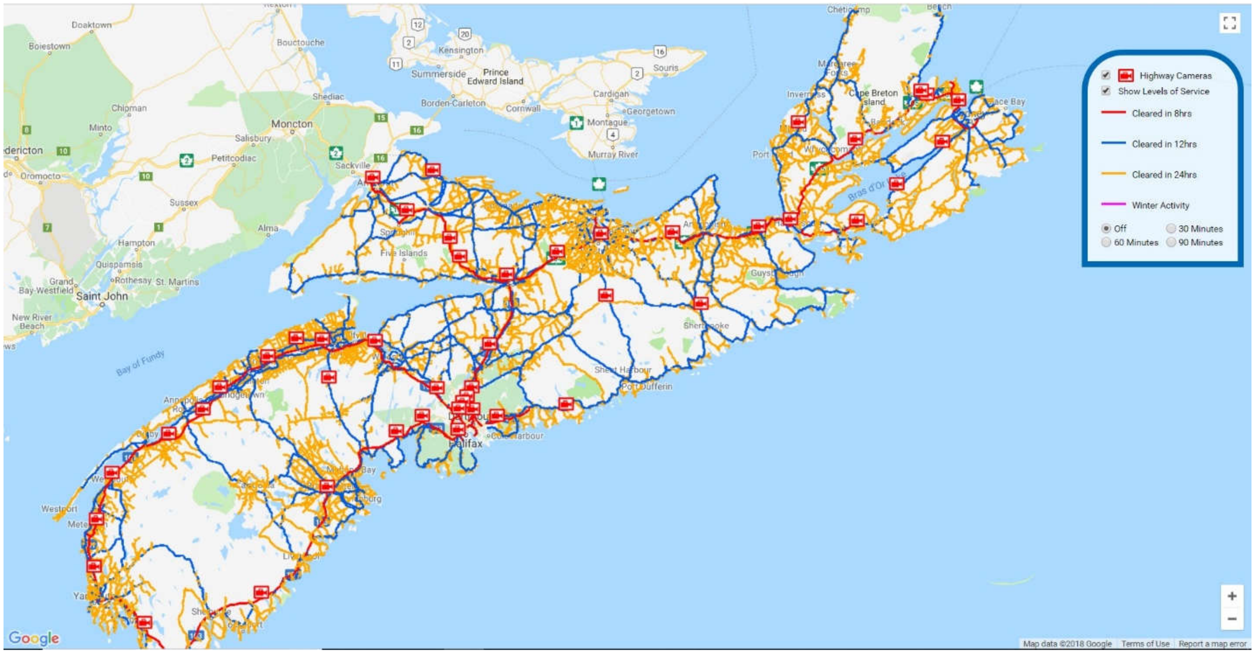

Figure 3-36 Plowtracker website showing various winter operation details in Nova Scotia (Transportation and Infrastructure Renewal, 2018)

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 3-37.

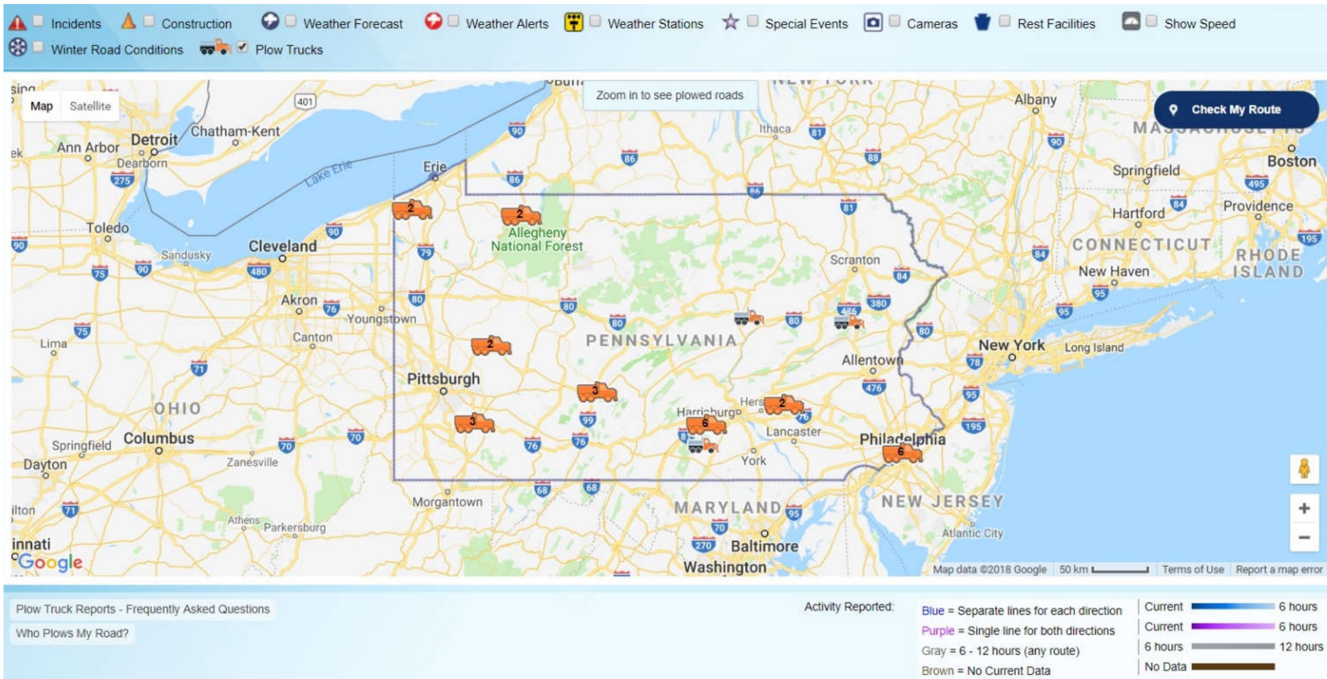

Figure 3-37 "511 Pennsylvania snowplow tracker system" showing the locations of snowplow trucks their past routes (511PA, 2018)

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).

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).

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 3-38.

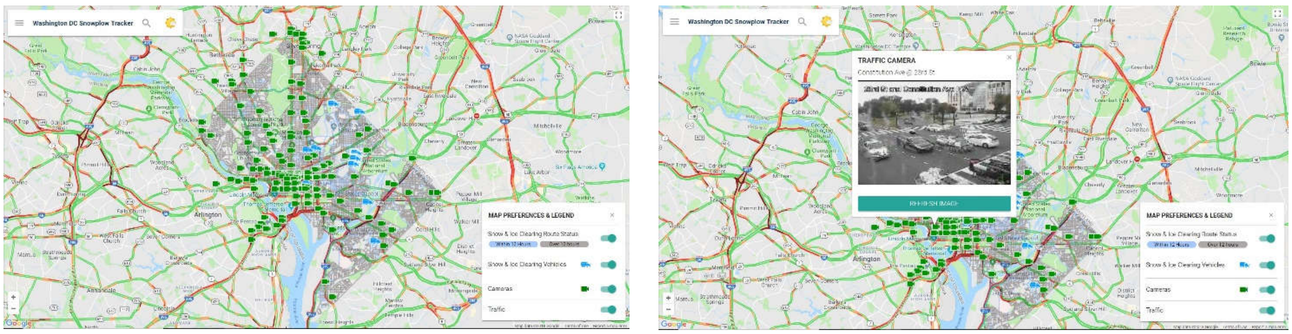

Figure 3-38 District's Automated Vehicle Locator (AVL) system in Washington DC showing the locations and traffic camera views of winter operations vehicles of DC (District Snow Team, 2018)

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 3-39 and Figure 3-40 show the interface of the MI Drive website.

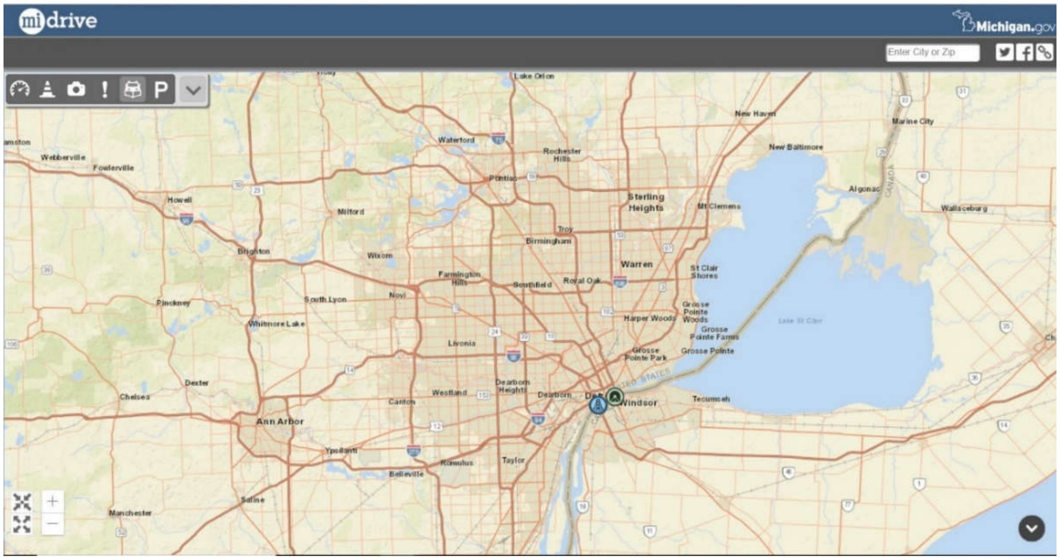

Figure 3-39 Interface of MDOT's MI Drive website (MI Drive, 2018)

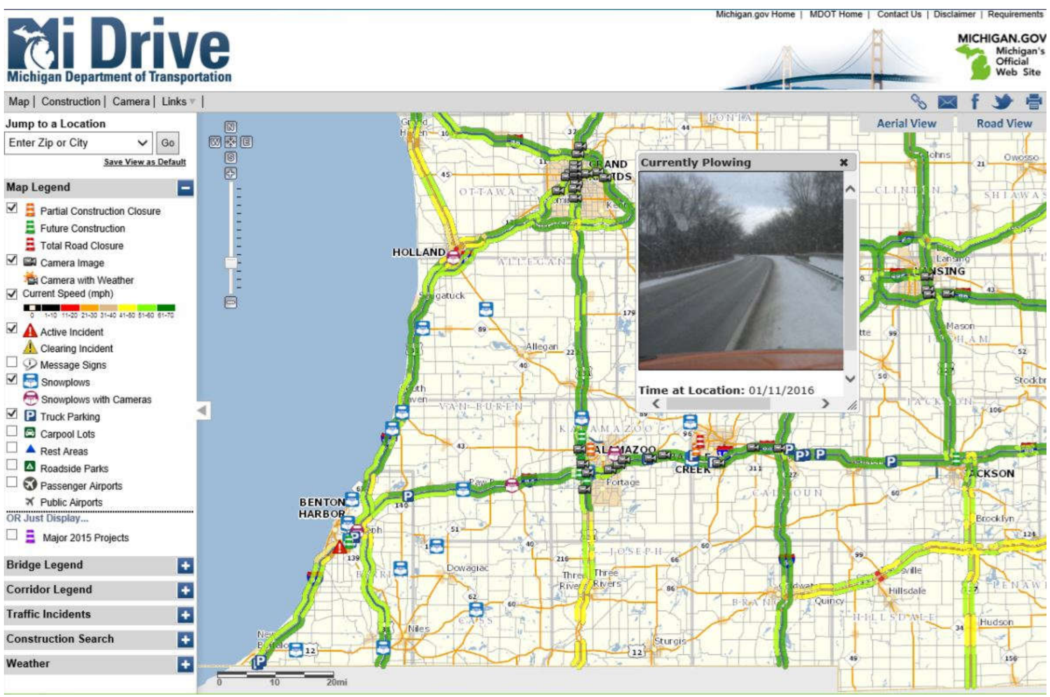

Figure 3-40 Interface of MDOT's MI Drive website showing camera view of an active winter operations vehicle (Cook, 2016)

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).

The City of Minot, North Dakota, has attached GPS chips to its vehicles involved with winter operations. All information on winter operations information is 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 3-41 shows the "City of Minot" website for information regarding winter operations.

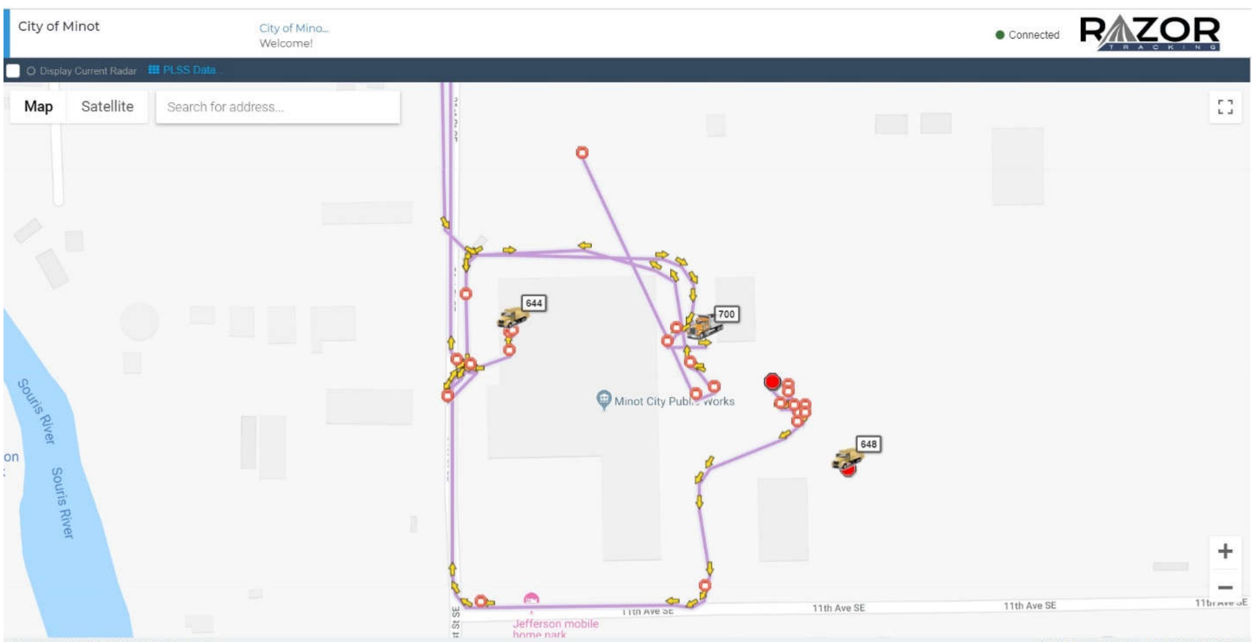

Figure 3-41 City of Minot website for information regarding winter operations (Razor tracking, 2018)

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).

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 the ASP cab-mounted display. The system received data from the snowplows' collision-warning system that was installed on the vehicles. Radar sensing assisted drivers in finding the road and obstacles that could be in the way of the plow (FHWA, 2001). An ASP setup is shown in Figure 3-42.

Figure 3-42 ASP Human-Machine Interface is mounted on the windshield of a Caltrans snowplow (FHWA, 2001)

The Texas Department of Transportation (TxDOT) uses the "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).

3-9 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 3-43, 3-44, 3-45, and 3-46 (Laserline, 2018).

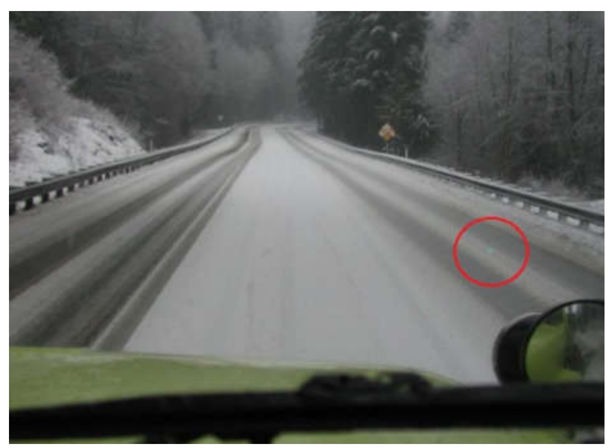

Figure 3-43 Laser path guidance system illustration and actual laser projection on the road from a winter operations vehicle (Laserline, 2018)

Figure 3-44 Two different winter operations vehicles with laser projection equipment installed on them (Laserline, 2018)

Figure 3-45 Laser control box inside of vehicles (Laserline, 2018)

Figure 3-46 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 employs 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 to keep away from hitting mailboxes. Many mailboxes have been toppled by snowplow blades in past snow removal operations (Northern Virginia Daily, 2015). Figure 3-47 shows a laser mounted on top of a snowplow truck.

Figure 3-47 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)

3-10 SUMMARY

Table 3-5 summarizes the methods and devices to enhance the safety of winter operations vehicles during winter weather operations based on the literature review.

Table 3-5 Evaluation of Methods and Devices for Safety Applications in Winter Weather Operations (Shahandashti et al., 2019)

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

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 4
ACCUMULATION OF SURVEY RESPONSES

4-1 ACCUMULATION OF SURVEY RESPONSES

The survey questionnaire was distributed among all the 50 states of the U.S., as well as amongst 25 Texas Department of Transportation (TxDOT) districts to sample the extent of inconsistencies of winter weather operations. Representatives from 26 states responded to the survey. Figure 4-1 illustrates the surveyed states.

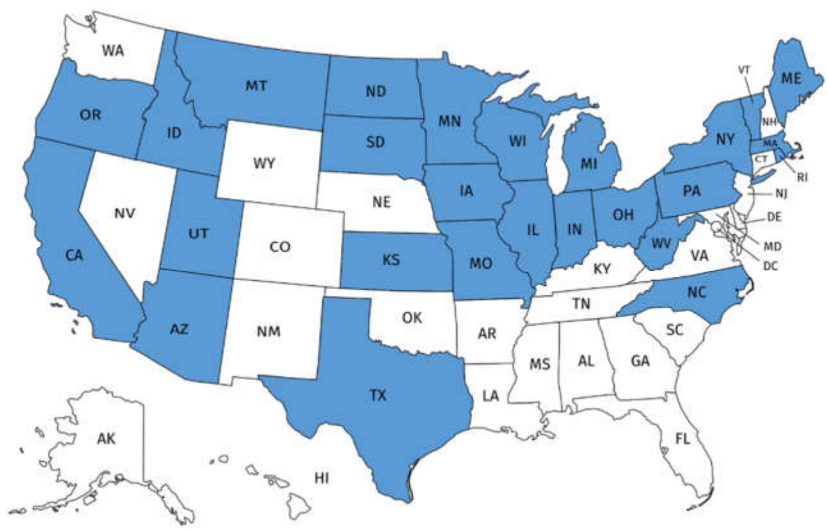

Figure 4-1 Survey results collected from 26 states of the U.S. (Shahandashti et al., 2019)

Representatives from 15 TxDOT districts of Texas also responded to the survey. Figure 4-2 illustrates the positions of respondents from the 26 states and 15 districts of Texas. The variety of positions enabled us to create a unique analysis of the feedback of the maintenance personnel who are directly involved with winter weather operations.

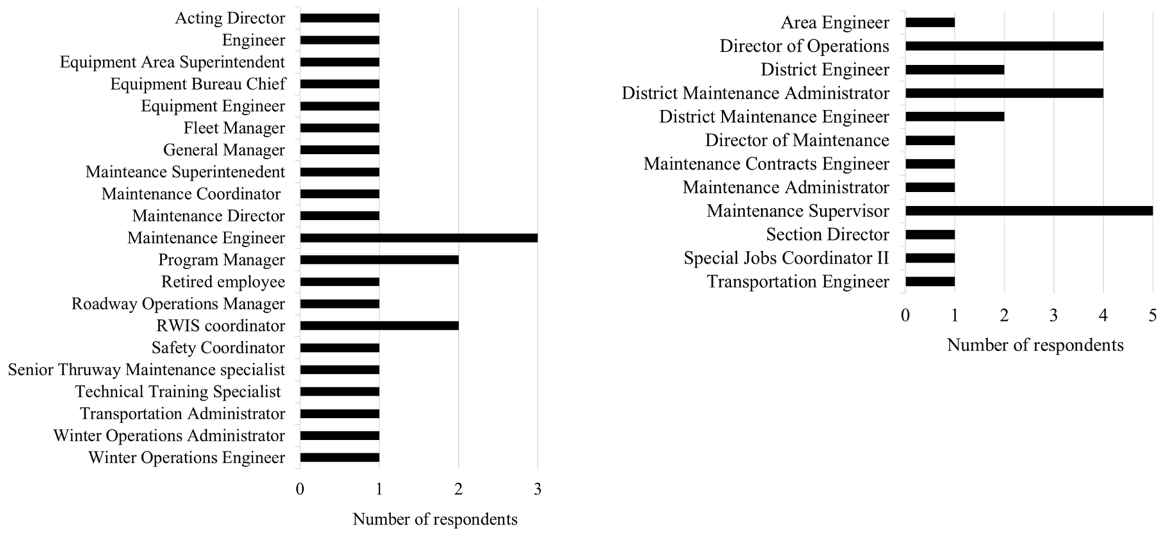

Figure 4-2 Positions of respondents from 26 states (left) and 15 districts of Texas (right) (Shahandashti et al., 2019)

Through the surveys, this research sampled information about safety applications in winter weather operations in more than half of the states in the U.S. and half of the districts in Texas.

4-1-1 General Information

Figure 4-3 illustrates the information received from survey responses regarding the usage of shadow vehicles in the US. Shadow vehicles are moving trucks spaced a short distance from a moving operation, giving physical protection to workers from traffic approaching from the rear. It can be observed that the majority of the states do not use shadow vehicles.

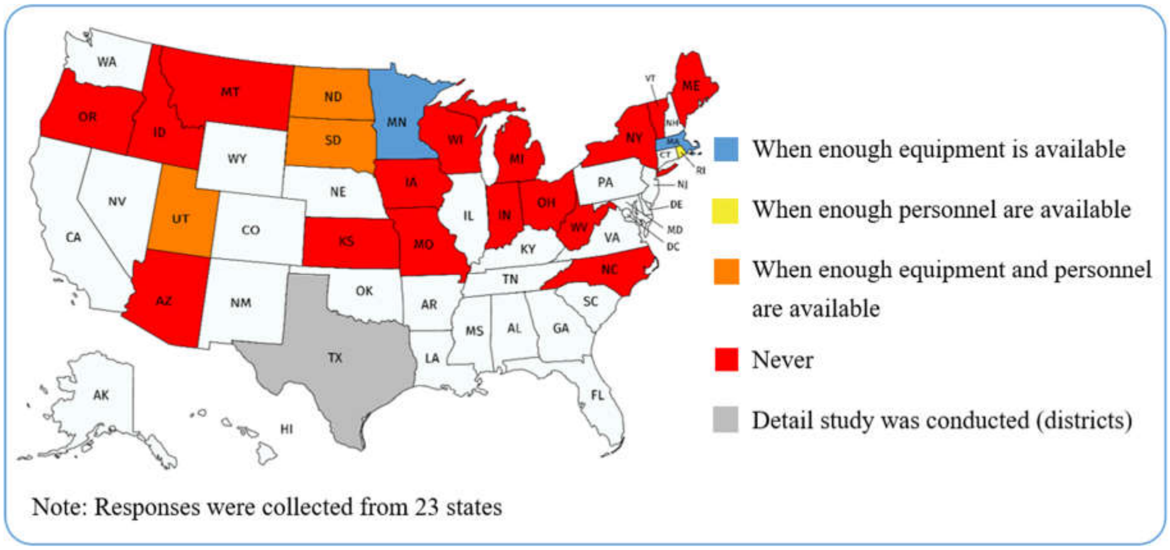

Figure 4-3 Shadow vehicle usage in different states of the US (Shahandashti et al., 2019)

Figure 4-4 shows the usage of shadow vehicles in different TxDOT districts. Even within a single state, the districts do not follow a consistent method for operating their shadow vehicles.

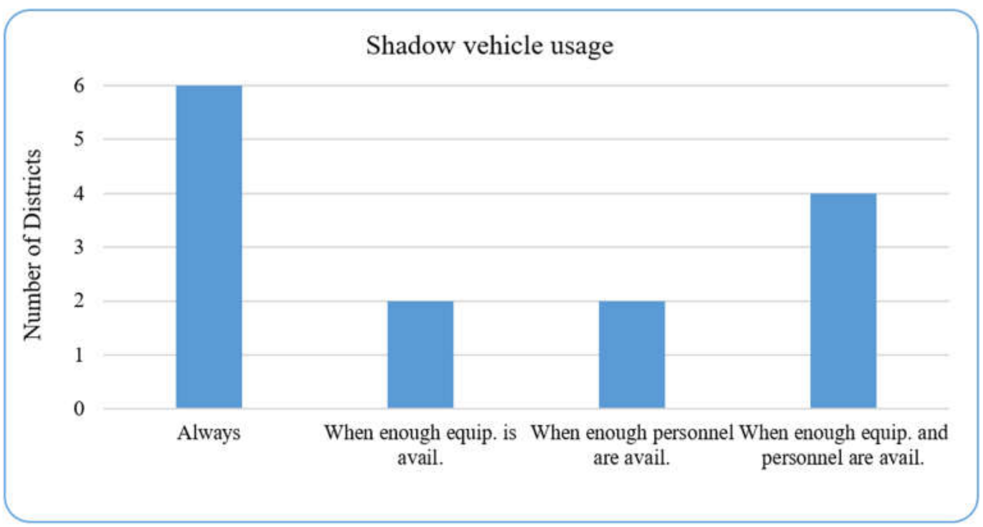

Figure 4-4 Shadow vehicle usage in different TxDOT districts (Shahandashti et al., 2019)

Along with the information regarding shadow vehicles, pictures were collected of winter operations vehicles used by various US states as well as by the district offices of TxDOT were also collected. The images of the winter operations vehicles used in Indiana, Iowa, Kansas, North Dakota, Oregon, Utah as well as two districts of Texas are shown in Figures 4-5, 4-6, 4-7, 4-8, 4-9, 4-10, 4-11, 4-12, 4-13 and 4-14, respectively.

Figure 4-5 Front view of winter operations vehicles of Indiana (Shahandashti et al., 2019)

Figure 4-6 Back view of winter operations vehicles of Indiana (Shahandashti et al., 2019)

Figure 4-7 Front (left) and back (right) views of winter operations vehicles of Iowa (Shahandashti et al., 2019)

Figure 4-8 Front (left) and back (right) views of winter operations vehicles of Kansas (Shahandashti et al., 2019)

Figure 4-9 Front (left) and back (right) views of winter operations vehicles of North Dakota (Shahandashti et al., 2019)

Figure 4-10 Back view showing wing plows of winter operations vehicles of North Dakota (Shahandashti et al., 2019)

Figure 4-11 Front (left) and back (right) views of winter operations vehicles of Oregon (Shahandashti et al., 2019)

Figure 4-12 Back view showing wing plows of winter operations vehicles of Utah (Shahandashti et al., 2019)

Figure 4-13 Back view of a winter operations vehicle of TxDOT (Shahandashti et al., 2019)

Figure 4-14 Front (left) and back (right) views of a winter operations vehicles of TxDOT (Shahandashti et al., 2019)

4-1-2 Warning Lights

Throughout the states of the US, amber is the most common color of warning lights. However, most states use a combination of other colors with amber. Significant differences in the usage of warning lights were found in the aspects of position, pattern, types, and others. The survey results from 23 states (three states did not provide information regarding warning lights) on the evaluation of warning lights are summarized in Figure 4-15.

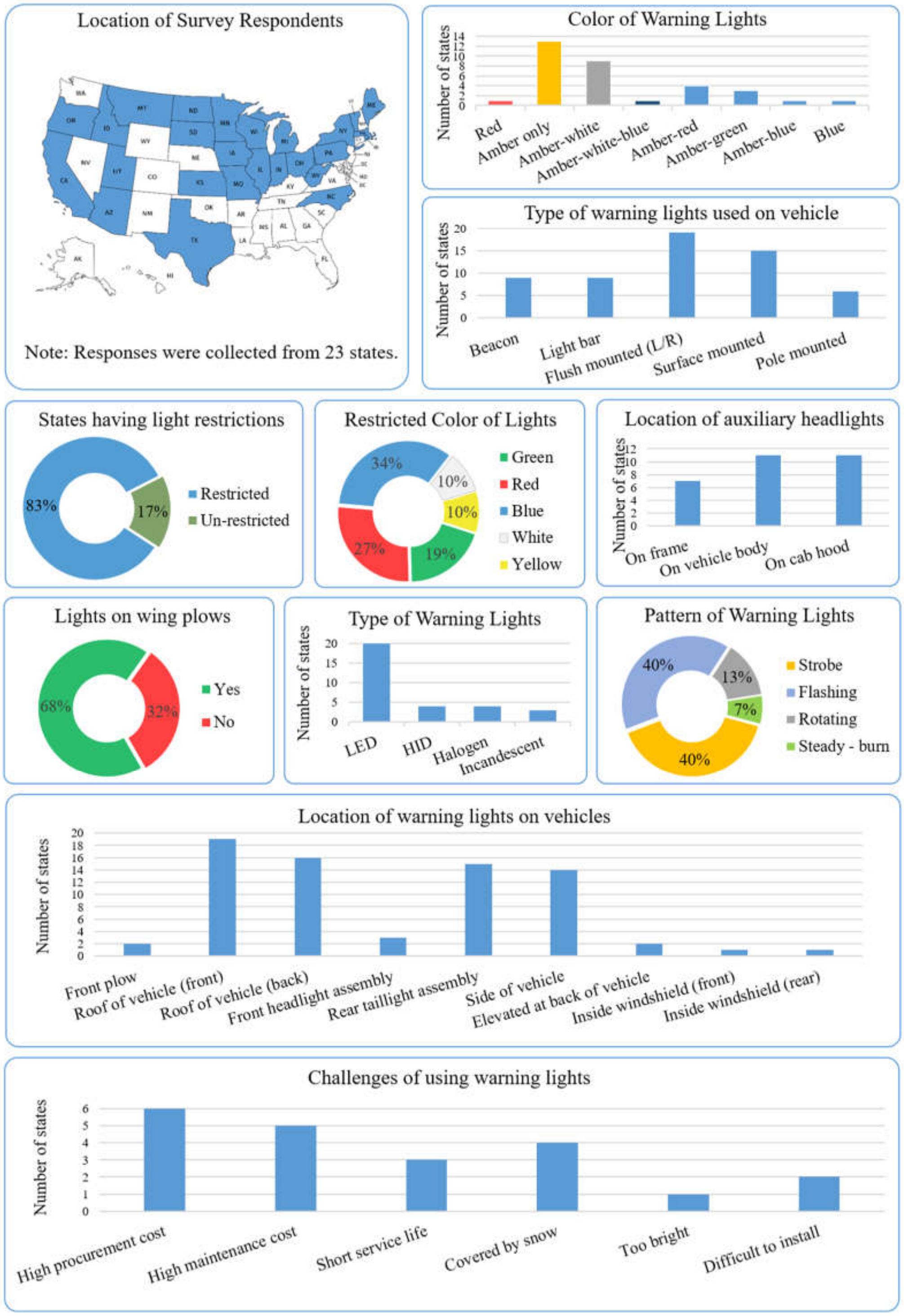

Figure 4-15 Survey results of the states of the US on the evaluation of warning lights on winter operations vehicles (Shahandashti et al., 2019)

Survey results from the 15 TxDOT districts on the evaluation of warning lights are summarized in Figure 4-16. 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 4-16 Survey results of 15 TxDOT districts on the evaluation of the warning lights on winter operations vehicles (Shahandashti et al., 2019)

4-1-3 Heated Lens

Responses from 24 states and 12 TxDOT districts were collected in this section of the survey. The responses have been illustrated in Figure 4-18. The respondents from California, Kansas, Missouri, Montana, Ohio, Rhode Island, New York, and North Dakota have reported the high procurement cost of the lens as a challenge. None of the TxDOT districts use the heated lens as safety applications during winter weather operations (Shahandashti et al., 2019).

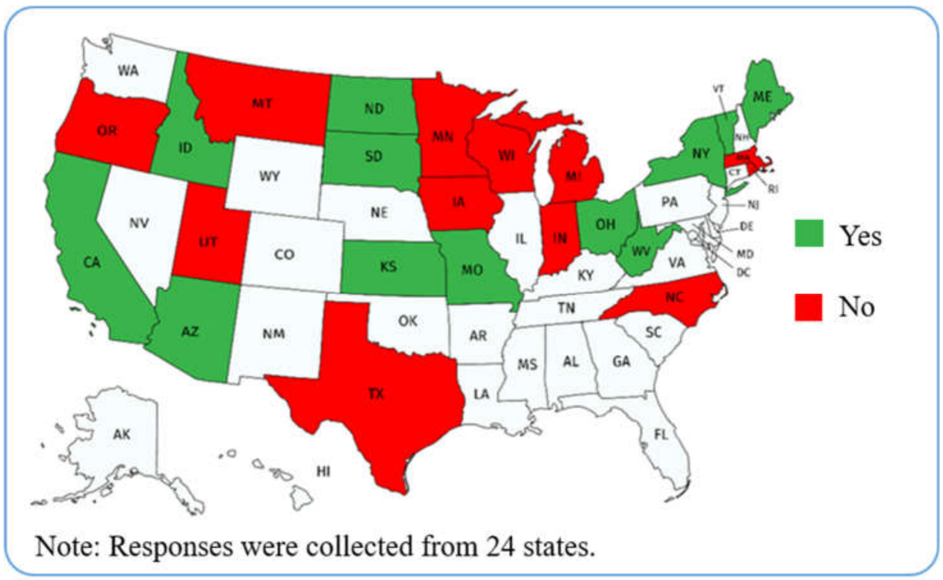

Figure 4-17 Use of heated lens in the states of the US (Shahandashti et al., 2019)

4-1-4 Message Signs

Responses from 24 states were collected in this section of the survey and summarized in Figure 4-18. The majority of the message signs 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. All the 24 states reported using digital message signs on their winter operations vehicles.

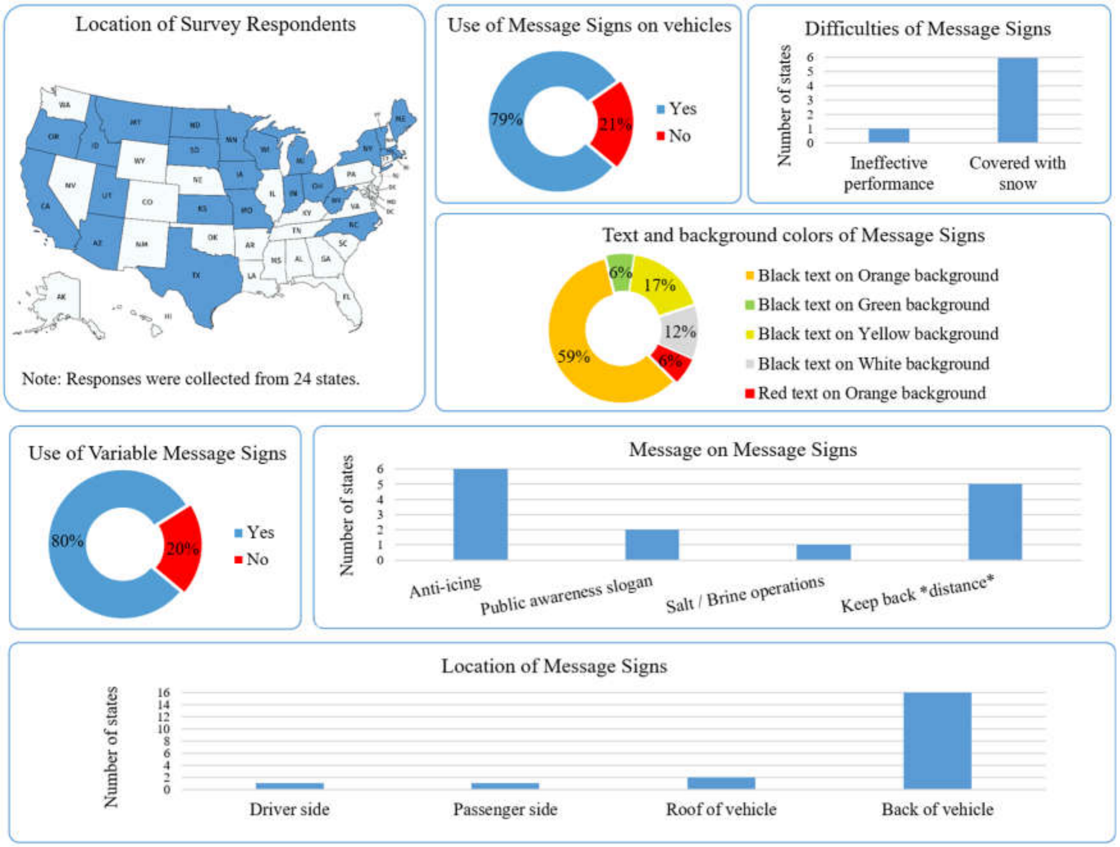

Figure 4-18 Survey results of the states of the US on the evaluation of message signs on winter operations vehicles (Shahandashti et al., 2019)

Responses from 15 TxDOT districts were also collected in this section of the survey and summarized in Figure 4-19. 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 reported using digital message signs on their winter operations vehicles (Shahandashti et al., 2019).

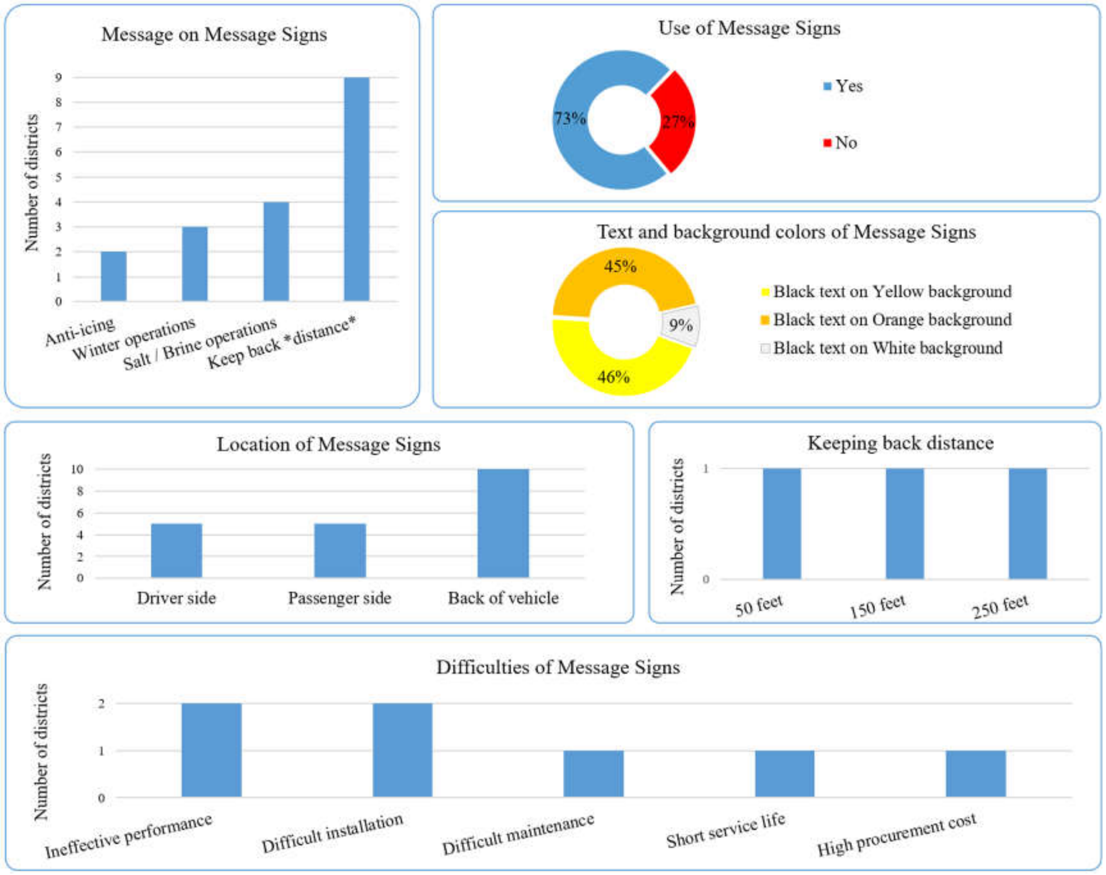

Figure 4-19 Survey results of 15 TxDOT districts on the evaluation of message signs of winter operations vehicles (Shahandashti et al., 2019)

4-1-5 Retroreflective Markings

Responses from 24 states on the use of retroreflective markings are summarized in Figure 4-20. Respondents in six states indicated that they do not use these markings. In the other states, red is the most common color used for the markings, although other colors like white and yellow are used very frequently as well. The reported difficulties of retroreflective markings were short service life, as well as snow sticking to their surfaces.

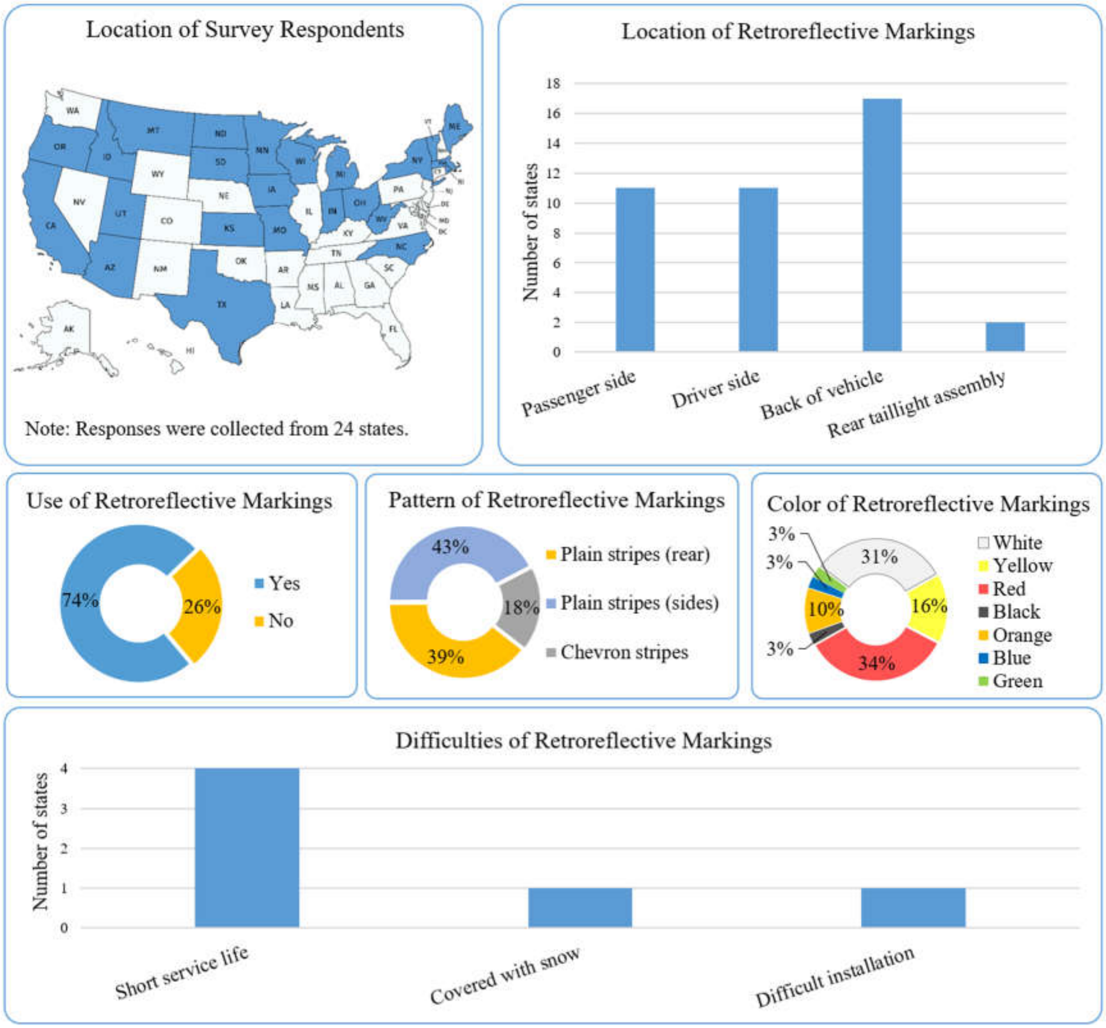

Figure 4-20 Survey results of the states of the US on the evaluation of retroreflective markings on winter operations vehicles (Shahandashti et al., 2019)

The responses from 14 TxDOT districts were also collected in this section of the survey and summarized in Figure 4-21. 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 4-21 Survey results of 14 TxDOT districts on the evaluation of retroreflective markings on winter operations vehicles (Shahandashti et al., 2019)

4-1-6 Rear Airfoils

Responses from 24 states were collected in this section of the survey (Figure 4-22). Airfoils were reported to be ineffective during snow conditions, especially when the snowfall is heavy and wet. The New York respondent reported high maintenance costs for the airfoils as well. The respondent from Utah reported that the airfoils could be damaged while loading materials on the operations vehicles.

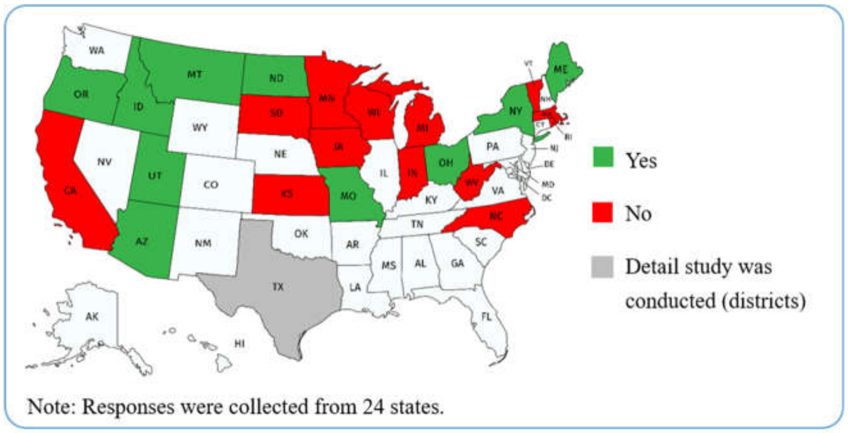

Figure 4-22 Use of rear airfoils in the states of the US (Shahandashti et al., 2019)

Responses from 14 TxDOT districts were also collected in this section of the survey and summarized in Figure 4-23. Only one district reported using rear airfoils as a safety application in winter weather operations. The airfoils were reported to be ineffective during snow conditions.

4-1-7 Wind Deflectors

Responses from 25 states of the US and 12 TxDOT districts were collected in this section of the survey (Figure 4-23). Survey results showed that none of the Texas districts use wind deflectors as safety applications in winter weather operations (Shahandashti et al., 2019). The respondents from the states that use the wind deflectors have reported that the deflectors are inefficient during the performance.

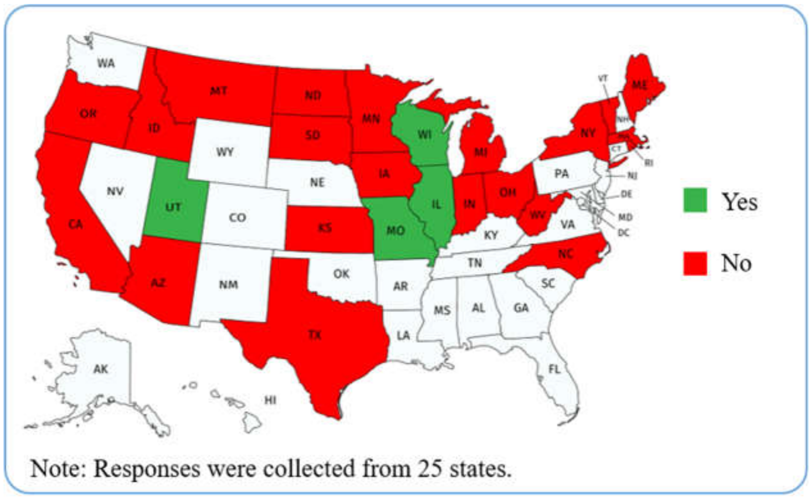

Figure 4-23 Use of wind deflectors in the states of US (Shahandashti et al., 2019)

4-1-8 Smart Snowplow Systems

Responses from 25 states on the evaluation of smart snowplow systems are illustrated in Figure 4-24. Different states use a multitude of smart systems to aid in winter operations. The high procurement and maintenance costs are the leading challenges for the utilization of smart snowplow systems.

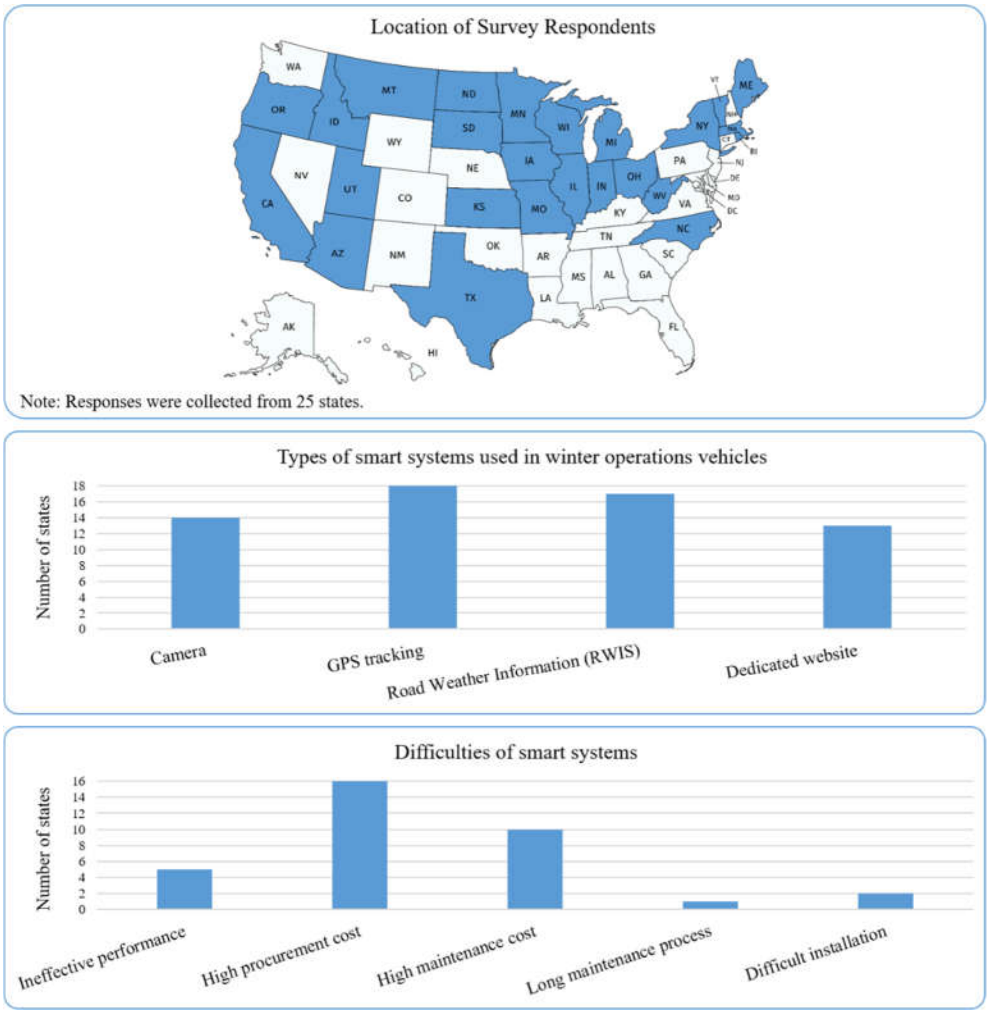

Figure 4-24 Survey results of the 25 states on the evaluation of the smart system on winter operations vehicles (Shahandashti et al., 2019)

Responses from 13 TxDOT districts were also collected in this section of the survey. 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.

4-1-9 Laser Guided Snowplows

Responses from 26 states of the US and 12 TxDOT districts were collected in this section of the survey (Figure 4-25). Survey results showed that none of the Texas districts use laser-guided snowplows in winter weather operations.

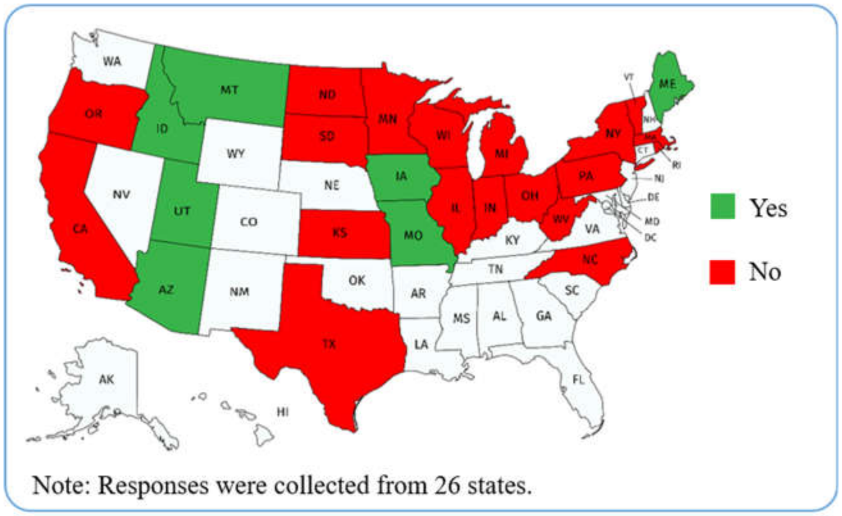

Figure 4-25 Use of laser guided snowplows in the states of US (Shahandashti et al., 2019)

4-1-10 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 from the 26 U.S. states.

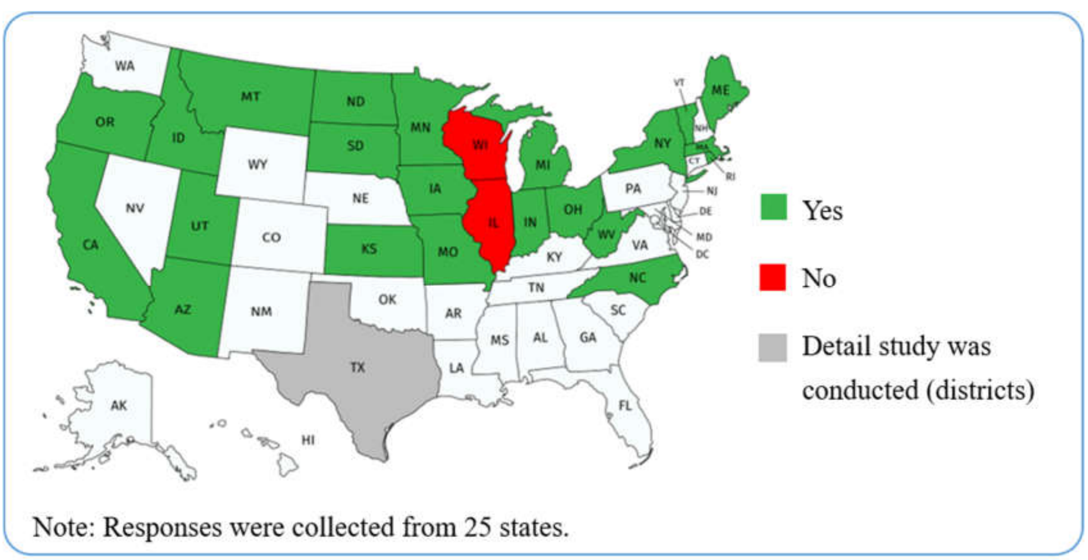

Figure 4-26 States who are willing to participate in follow-up interviews (Shahandashti et al., 2019)

Of the 15 TxDOT districts, 7 districts responded positively to participate in follow-up interviews (Shahandashti et al., 2019).

4- 2 DISCUSSION OF SURVEY RESPONSES

The survey was designed to gather information regarding existing methods and devices used for enhancing the safety of winter weather operations of the 50 states of the U.S as well as within 25 TxDOT districts. Emails were sent to 123 maintenance personnel within 50 states of the U.S., and all 25 TxDOT districts where emailed as well. Responses where collected from 26 individuals within 49 states (excluding Texas), with a successful response rate of 21.38% (Shahandashti et al., 2019). Within the districts of Texas, responses where collected from 15 individuals within the 25 districts, with a successful response rate of 60%.

Each state of the U.S. has their own state Departments of Transportation (DOTs). Through the surveys, it was found that currently there are no standardized guidelines throughout the US about the methods of visibility of winter operations vehicles. As a result, variations within the methods through different states could be result of the lack of a centralized set of guidelines. Through the surveys, it was also found that the districts of Texas are using various methods for the visibility of winter operations vehicles. Many of the visibility methods were not consistent, even amongst neighboring districts. In order to gain further insight regarding the inconsistencies between the different districts of a single state, the research team conducted follow-up interviews with TxDOT maintenance personnel. Details about the interviews has been discussed in the following chapter.

CHAPTER 5
INTERVIEWS

The survey results showed a wide range of inconsistencies within the methods of visibility of winter operations vehicles. Differences were found within different states. However, significant differences in the methods were found within a single state (Texas) as well. In order to gain further insight regarding the inconsistencies between different TxDOT districts, the research team conducted follow-up interviews with TxDOT maintenance personnel. These interviews were aimed to identify the interviewee's best practices and lessons learned from real projects. Selection of interviewees, instructions for interviews, interview questions, and interview results have been presented in this chapter.

5-1 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.

5-2 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.

5-3 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?

5-4 INTERVIEW RESULTS

In total, the research team conducted interviews with respondents from six TxDOT districts (Shahandashti et al., 2019). 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.

5-4-1 Interviewee Number 1

The average speed of winter operations vehicles was reported to be 55 miles per hour. The vehicles use chevron striped retroreflective markings (fluorescent), and truck-mounted attenuators (TMA) (when enough employees and equipment are available) for precaution and preparation against collisions. The vehicles are monitored using "Network fleet," a software that shows the location of the plows via GPS (updating every 10 to 30 minutes). Despite these precautions, the interviewee reported that their winter operations vehicles frequently get hit from the rear due to low visibility in snow. Most of the collisions occur in the passing lanes. The shortage of employees and equipment makes the operations very risky. It was also reported that the district does not have any means of informing the public (such as Dynamic Message Signs (DMS), radio broadcast, etc.) about the location of ongoing winter operations. For better safety of winter operations, the interviewee suggested improvements on the methods of reducing snow adhering to the surfaces of winter operations vehicles. Additionally, the interviewee also wanted methods to eliminate the necessity for single person operations (due to shortage of employees and equipment).

5-4-2 Interviewee Number 2

The winter operations vehicles were reported to be followed by a “shadow vehicle” during the operations. The vehicles have message signs with black text over yellow background, along with red & white or red & yellow chevron striped retroreflective markings. The district office uses Dynamic Message Signs (DMS) to communicate with commuters about winter weather operations. The vehicles are monitored (by the district office) online using “Network fleet”. The interview reported that commuters try to speed up and overtake the winter operations vehicles, which increases the risk of collision. The interviewee also reported that LED lights are less visible during the daytime. For improvements, it was suggested that the lights are mounted high above the vehicles to avoid snow/dirt accumulation, resulting in better visibility. Additionally, it was suggested that wet pre-treatment could reduce dust adhering to the warning lights and retroreflective markings.

5-4-3 Interviewee Number 3

The winter operations vehicles were reported to use amber-blue colored warning lights, red & white chevron striped retroreflective markings, message signs with black text over the orange background as well as truck-mounted attenuators (TMA) for precaution and preparation against collisions. The interview reported that although bright warning lights were helpful in identifying winter operations vehicles during the daytime, the lights can cause “light-gazing” amongst commuters during nighttime. “Light-gazing” leads to unsafe driving and increases the possibility of rear-end collisions. Additionally, it was reported that during the most adverse winter weather conditions, it becomes essential for maintenance officials to work in 14-hour shifts. These shifts become very stressful for officials. It was suggested that district offices have an arrangement for maintenance personnel to be able to shower and rest during the most adverse winter weather conditions.

5-4-4 Interviewee Number 4

The interviewee reported that 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. For safer winter operations, the interviewee suggested that the 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. Additionally, existing environmental sensors could be integrated with the Road Weather Information System (RWIS). The system and its components should be easy to maintain.

5-4-5 Interviewee Number 5

The winter operations vehicles were reported to use amber-blue colored warning lights, red & white chevron striped retroreflective markings, and message signs which instruct drivers to stay back a distance of 250 feet. with black text over the orange background as well as truck-mounted attenuators (TMA) for precaution and preparation against collisions. The interview reported difficulty regarding the additional time required by the maintenance crew to clean the vehicles properly after each operation. It was suggested that implementing smart systems that can acquire data like road surface temperature, ambient temperature, and wind speed in real time could help the district office utilize winter operations resources effectively.

5-4-6 Interviewee Number 6

The winter operations vehicles were reported to use dimmable warning lights, arrow boards, and rear airfoils for precaution and preparation against collisions. Arrow boards are used instead of message signs (message signs are too big to fit the vehicles) on the back of V-boxes to inform commuters about the presence of the winter operations vehicles. It was reported that during the most adverse winter weather conditions, it becomes essential for maintenance officials to work in 16-hour shifts. During severe snowstorms, other districts provide additional winter operations vehicles and equipment for support. However, the inconsistent appearance of vehicles and equipment of different districts lead to inefficiencies in collaborated winter operations. The interviewee suggested using elevated warning lights, heated lens, smart systems, and consistent appearance of the winter operations vehicles for better safety of the maintenance crew as well as the traveling public during adverse snow conditions.

CHAPTER 6
DISCUSSION OF RESULTS

After the survey was distributed to gather information regarding visibility methods of winter weather operations, responses where collected from 26 individuals within 49 states of U.S. (excluding Texas), with a successful response rate of 21.38%. Within the 25 districts of Texas, responses where collected from 15 individuals, with a successful response rate of 60%.

The survey responses demonstrated a wide array of dissimilarities within the visibility methods of winter operations vehicles. Various districts within a single state (Texas) also showed inconsistencies amongst these methods. Through detailed interviews, it was conferred that the inconsistent methods caused significant challenges during winter operations. Warning lights of different colors, patterns, locations, and intensities are used throughout the states of U.S. LED lights were reported to be the most common type of warning light. However, several states reported the inefficiency of these lights due to snow and ice accumulation on them during operations. It was reported that the message signs on the back of the winter operations vehicles have several variations of colors (text and background). “Arrow boards” were reported to be used instead of message signs as well. The research team observed many differences in the colors and patterns of retroreflective markings. Many states reported using smart systems for enhancing the safety of their winter weather operations. Components of smart systems such as road surface temperature sensors and ambient air temperature sensors were reported to be extremely helpful. Dry sheds were reported to be beneficial during the loading and unloading of de-icing materials on operations vehicles, ensuring efficient utilization of the maintenance crew. The research team also observed the fatigue the winter weather operations bring to the maintenance personnel, especially during the worst snow storms when 12 to 14 - hour shifts become essential for clearing roadways of affected areas.

CHAPTER 7
RECOMMENDATIONS AND CONCLUSION

7-1 CRITICAL ANALYSIS

The data collected from the literature review, survey questionnaire, and interviews have been analyzed in this chapter. Through an extensive literature review, a detailed understanding was obtained of methods used to increase the visibility of winter operations vehicles in the US. By conducting two surveys (one for all states of US and another for all TxDOT districts), responses were collected from 26 states and 15 TxDOT districts. The survey was followed by interviews with respondents from six districts. After evaluating the survey responses and the interviews, the best safety practices in winter weather operations were identified.

7-2 RECOMMENDATION OF BEST PRACTICES

After the evaluation of safety practices in winter weather operations, the most effective methods were identified (Shahandashti et al., 2019). They are as follows:

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

- The author recommends 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 7-1.
    - The author recommends that all warning lights have options to be dimmed and turned on/off by the operator.

Figure 7-1 Recommended amber and blue color warning lights on top of winter operations vehicle (Shahandashti et al. 2019)

- The author recommends 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 7-2.

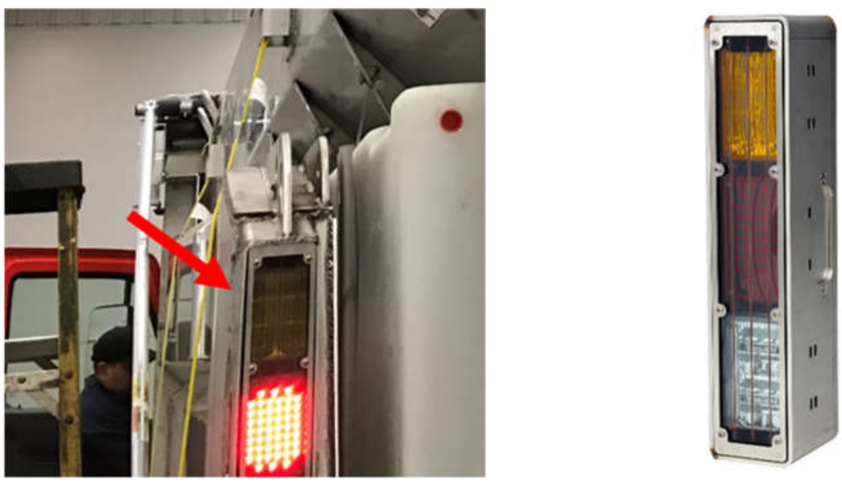

Figure 7-2 Recommended heated lens used with warning lights (Kansas) (Shahandashti et al. 2019)

- The author recommenda that message signs have "black text over the 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 7-3).

Figure 7-3 Recommended message signs on the back of winter operations vehicles (Shahandashti et al., 2019)

  - The author recommends 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 7-4).

Figure 7-4 Recommended arrow board on the back of a winter operations vehicle (Shahandashti et al. 2019)

- The author recommends 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 7-5.

Figure 7-5 Recommended retroreflective markings on the back of winter operations vehicles (Paris (left), Wichita Falls (middle) and Dallas (right) Districts) (Shahandashti et al. 2019)

- The author recommends 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 author recommends that each TxDOT district has a dry shed (permanent or temporary) to ensure efficient loading of salt and brine on to winter operations vehicles. Examples of dry sheds from states of Virginia and Massachusetts are shown in Figure 7-6.

Figure 7-6 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 author recommends that each 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 author recommends 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.

CHAPTER 8
CONCLUSION AND FUTURE WORK RECOMMENDATION

8-1 FUTURE WORK

The study's findings demonstrate that there are striking dissimilarities within the methods for visibility of winter operations in various states in the U.S. Even within one state (i.e., Texas), considerable differences were identified. Dissimilarities include variations in colors of warning lights, message signs, and retroreflective markings. Dissimilar smart systems were also identified within the operations. The inconsistencies in the implementation of these methods confuse the public who are traveling in winter conditions when visibility is low. The confusion leads to a delay in perception time and response time of the drivers and eventually, leads to rear-end collisions with the winter operations vehicles.

Within the survey, respondents were asked about new and innovative technologies they have experience of using technologies to enhance the visibility of winter weather operations. Respondents from Iowa reported using air puffers (compressed air) to keep the warning lights clear of snow. Respondents from Indiana reported using an environmental sensor, for receiving on-site information such as mobile friction, air temperature, surface temperature, and humidity. Respondents from Illinois reported using lighted plow markers. The winter operations vehicles in the state of Montana use programmable brake lights to pulse or flash when braking or using turn signals. Respondents from Minnesota reported using heads up displays so that the vehicle operators could navigate in low visibility situations. Future research could focus on these innovative technologies, and study its effectiveness for reducing collisions involving winter weather operations.

8-2 CONTRIBUTIONS TO THE STATE OF KNOWLEDGE

The findings of this research enhance the current state of understanding of methods for enhancing the visibility of winter operations vehicles. This research contributes to the state of knowledge by (1) evaluating the consistency of the methods of visibility used by different state DOTs; (2) evaluating the consistency of the methods of visibility used by different districts within Texas; and (3) collecting feedbacks from on-site maintenance personnel about the challenges faced while implementing and using each method. The identified dissimilarities in methods for visibility of winter operations vehicles provide useful information to assist state DOTs in adverse road conditions, identify the most effective methods of winter operations visibility, and help them best serve the public and their staff.

8-3 CONTRIBUTIONS TO THE STATE OF PRACTICE

This research contributes to the state of practice 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 recommendations of this synthesis research provide the opportunity for managers and policy makers to improve the state of practice of winter weather operations methods. However, 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).

Having consistent methods for the conspicuity of winter operations vehicles is expected to save lives and prevent injuries in vehicle crashes on snowy, slushy, and icy roads (Shahandashti et al., 2019). The consistent methods could positively impact the areas of benefit of transportation such as safety, traffic and congestion reduction, reduced operations cost and customer satisfaction (Ashuri et al. 2014). Safe and efficient winter operations will also enhance infrastructure conditions, increase vehicle service life and reinforce transportation system reliability.

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