Use of Equipment Lighting During Snowplow Operations

Synthesis of Information

CLEAR ROADS

research for winter highway maintenance

Western Transportation Institute
Monte Vista Associates

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September 2015

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1. Introduction

Snowplow vehicles often perform in conditions of limited visibility. Visibility is the ability of the operator to see the roadway ahead, which is influenced by weather conditions (primarily precipitation type and intensity), time of day, and the lighting systems on the plow vehicle. Lighting systems on snow-plow vehicles also provide conspicuity, or immediate recognition, by other roadway users. Supplemental warning lights of different configurations and placement, including on the sides of vehicles, increase the ability of other drivers to immediately recognize a snowplow vehicle. This is a critical safety measure because snowplow vehicles are usually moving at slower speeds than other traffic during winter maintenance operations which can be potentially hazardous to other motorists who get too close. Providing sufficient forward illumination for the snowplow vehicle operator in adverse conditions and a high level of conspicuity of the truck itself is a major concern of agencies responsible for snow and ice control.

Despite the recent development and availability of various types of headlights, work lights, and warning light technology, a large number of crashes are still attributed to the inadequate conspicuity of winter maintenance vehicles. For instance, Ohio Department of Transportation (ODOT) reported 63 crashes statewide involving snowplows in just one month of winter (December, 2010), compared to 57 crashes in the previous winter (2009). Kent County, Michigan reports on average of six rear end snowplows related crashes every year. All these crashes are attributed to the inadequate conspicuity in rear-end of the snow plow vehicle. Agencies are still struggling to find the right balance between making trucks as visible to the following driver as possible and also not too bright that it can blind the following driver.

The goal of this research project is to summarize the best practices used by state Departments of Transportation (DOTs) and local public work agencies with regard to auxiliary headlights, work lights, and warning light technology specifically for snowplow vehicles, with applicability to all roadway maintenance vehicles used in all seasons. The objectives of this study are to: 1) summarize the state-of-the-practices of lights used and configurations and, 2) to make recommendations on the use of various lighting technologies and mounting techniques on snowplow vehicles.

2. Auxiliary Headlights

Auxiliary Headlights are typically used on the front of snowplow vehicles and provide supplemental illumination of the road surface during plowing. They also provide forward-lighting and directional signals when a raised plow obscures standard truck headlights. Despite the presence of auxiliary headlights, the operator’s visibility is often reduced due to back-scattered light reflected from the plow and airborne snow. The degree impact of visibility is influenced by the different aspects of the light source such as mounting position, type of bulb, wavelengths, intensities, lensing technologies, etc.

2.1 Types of Auxiliary Headlight Bulbs

Incandescent bulbs have been used for headlamps for over a century since the advent of the automobile. But in the last two decades automobiles, including trucks, increasingly use halogen, high-intensity discharge (HID) and light-emitting diode (LED) bulbs as light sources. In particular, LEDs are becoming more common in newer vehicles. A recent study showed that LEDs improved visibility by allowing for easier viewing of objects at greater distances compared to halogen bulbs (Figure 1). Additionally, color of the LEDs is closer to that of daylight, rather than the yellowish color produced from the halogen bulbs. In addition to these benefits, LEDs are very energy efficient and have long service life when compared to all other headlight bulbs (Park, 2014). While HID bulbs are a comparable light source to LEDs, they are not energy efficient and have a shorter service life.

Figure 1: Comparison between Halogen and LEDs lights with high and low beam (**www.truckinginfo.com**)

From the survey responses, halogen bulbs were identified as still widely used for auxiliary headlights by winter maintenance agencies; while LEDs were the second commonly used bulb type for auxiliary headlights. Some respondents noted that they are testing LEDs in some of their vehicles. Other respondents noted that their agencies are currently specifying LEDs for their new trucks, replacements, and retrofits. Incandescent and HID bulbs are not very commonly used by winter maintenance agencies. Analysis indicates that vehicle operators using halogen bulbs had mixed opinions about the performance of auxiliary lights. However, respondents using LEDs generally viewed performance positively which is consistent with the findings from the literature. In contrast, respondents using incandescent bulbs in their vehicles viewed their performance as poor. It should be noted that very few respondents using HID bulbs viewed their performance positively. Overall, winter maintenance agencies are moving towards LEDs in their vehicle for auxiliary headlights.

One of the notable disadvantages of LED auxiliary headlights is that they do not produce a lot of heat resulting in snow accumulation on the lights during snow events. Heated lens LED auxiliary headlights were offered as a solution to combat this issue. From survey responses, very few agencies reported using heated lens in their vehicles. During warm snow events (around 25°F or warmer) snow generally sticks on the lights and heated lens helps to melt the accumulated snow on the lens. However, in cold snow events (around 15°F) snow will likely not stick on light lens, in such cases, using heated lens can actually create a dome of ice over the LED lens Therefore, it is important to have a control switch that can turn on and off the heated lens based on the conditions.

2.2 Impact of Mounting Locations and Beam width on Visibility during Snowy Conditions

A safety issue faced by snowplow drivers is the light bounce-back from auxiliary headlights during adverse weather conditions. The type of lighting source and spectral power distribution (color) plays a significant role in reducing back-scattered light, while mounting position and beam spread of headlights offer more leverage to vehicle designers (Bullough and Rea, 2001) and help snowplow vehicle operators to reduce or minimizing discomfort and glare during snowy conditions. However, other studies did not find any significant advantages of color lights in reducing the back-scattered light during inclement weather conditions (Boelter and Ryder, 1940, Schreuder, 1976, Moore, 1998). This is consistent with the findings from survey respondents whom reduce the light bounce-back by altering the mounting position. From the survey responses, it can be also noted that auxiliary headlights are primarily located on the truck body followed by on the cab hood, and plow frame. In addition, some respondents also mentioned having auxiliary lights on the top of the front fenders, on the grill, and on top of headache rack.

A survey of New York State Department of Transportation (NYSDOT) snowplow operators found that the most effective solution to reduce back-scattered light was to place the auxiliary headlights away from the operator’s line of sight.

Figure 2 shows the results of the preferred mounting location for different weather conditions. As shown in Figure 2, bold line indicates the heavy and blowing snow conditions. For these conditions the operator’s prefer passenger wing lights (~80%) compared to driver wing lights (~30%). This clearly indicates that as the weather conditions deteriorate from clear to heavy blowing snow, operators prefer the passenger side mounted lights rather than driver side mounted lights (or lights away from their line of sight) (Eklund et al., 1997). Bullough and Rea (2001) suggest installing a passenger side auxiliary headlight and to provide a switch for operators to turn on the lights only during inclement weather conditions. In addition, operators prefer narrow-beam light sources (spot lamp) over the wide-beam light sources (flood lamps) to reduce the amount of back-scattered light.

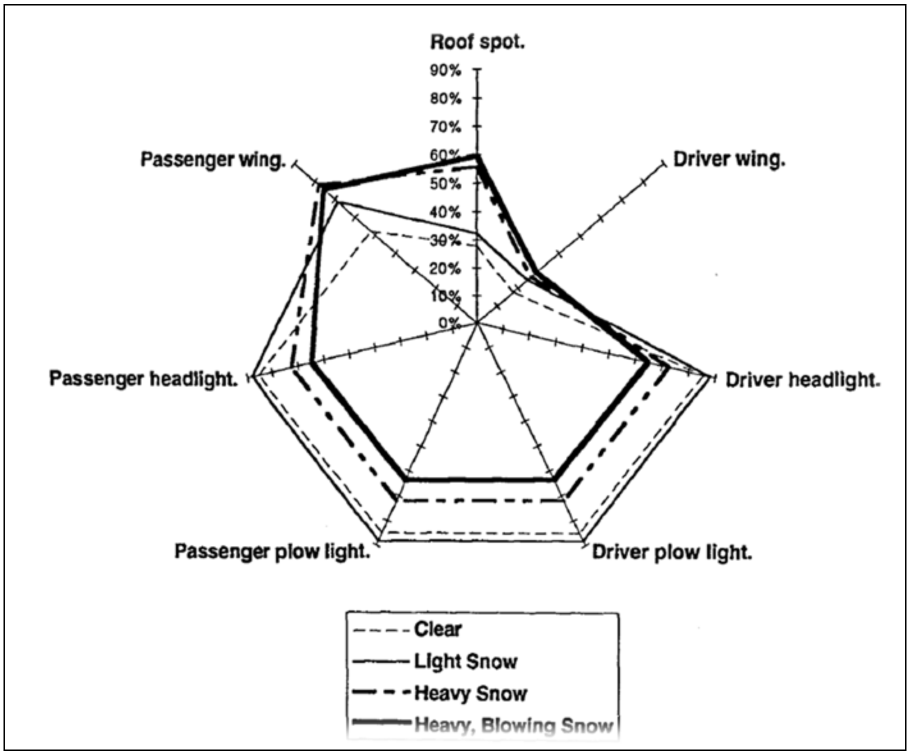

Figure 2: Percentage of operators using light under different weather conditions (Eklund et al., 1997)

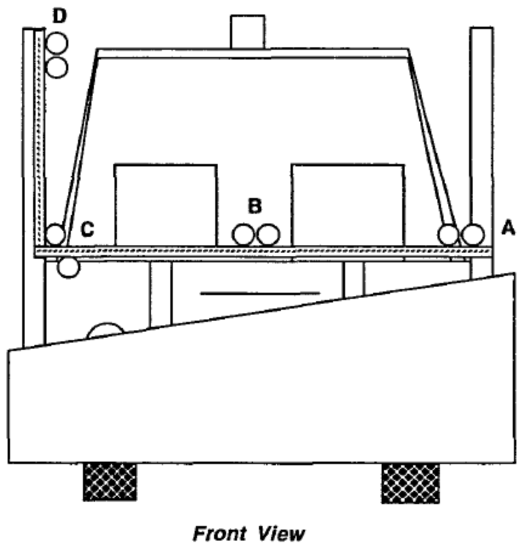

Figure 3: Mounting locations of test lamps at positions A through D. (Bullough and Rea, 1997)

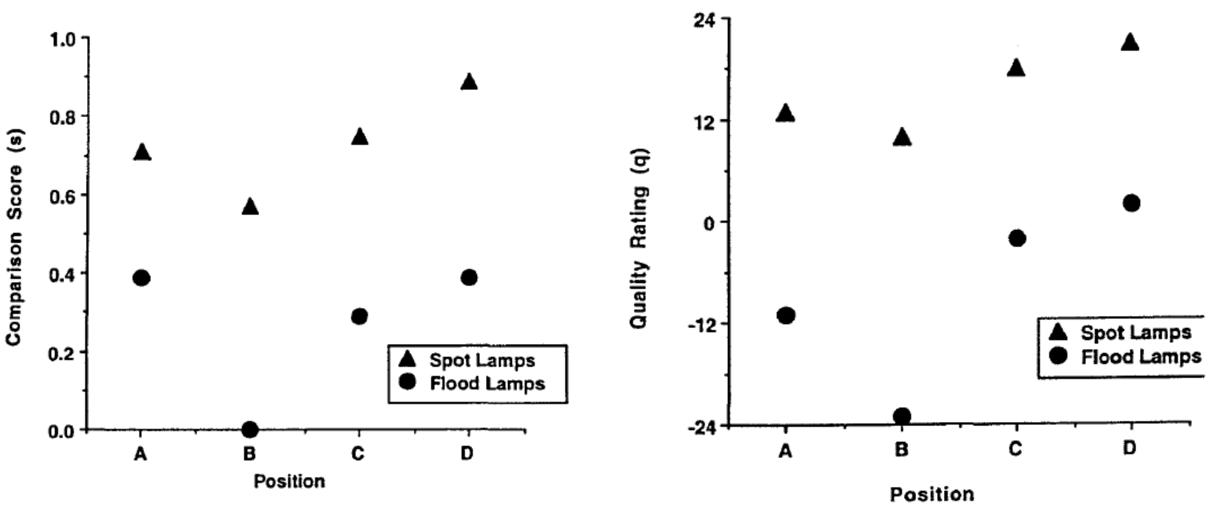

Figure 4: Comparison scores (left) and subjective quality rating (right) for spot lamps and flood lamps mounted in the locations shown in Figure 3. (Bullough and Rea, 1997)

In the same study, Bullough and Rea (1997) conducted a field study with NYSDOT snowplow operators at night during snow and freezing rain conditions to determine the impact of beam type and displacement from the operator's line of sight on visibility, glare, and satisfaction. Figure 3 shows the test snowplow vehicle used for field testing and Figure 4 shows the comparison scores and quality for each beam type and mounting locations. The findings from this field study are identical to the findings by Eklund et al. (1997) such that 1) a narrower spot lamp was preferred over the wide flood lamp and 2) mounting lamps away from the operator's line of sight (passenger side) was preferred over mounting lamps on the operator's line of sight (driver side). These findings are consistent with the findings such that operators are generally looking to move the auxiliary headlights away from their line of sight with narrow beams.

It can be safely concluded that mounting the auxiliary headlights away from operator's line of sight with narrow beams (spot light) reduces the light bounce-back during adverse weather conditions. There are other locations on a snowplow vehicle where auxiliary headlights can be mounted that are away from the operator's line of sight. For example, operators suggest mounting auxiliary headlights at the lowest possible place (above the plow or fender walls) which helps to avoid light bounce-back from the snow cloud created during plowing. One potential disadvantage of mounting auxiliary headlights at the lowest possible place (above the plow or fender walls) is the reflection of light from the back of the plow blade. This problem can be mitigated by using 1) black paint on the back of the plow blade and/or 2) narrow beam lights. Some operators also suggested mounting auxiliary headlights on the top corners of the plow blade which could provide the best visibility during falling snow. Potential disadvantages in mounting auxiliary headlights on the plow blade could include 1) snow sticking on lights, 2) decreased reliability of lights due to extreme vibration of the plow blade and 3) installation and wiring difficulties. While very few survey respondents suggested mounting auxiliary headlights on the top of the cab or headache rack, this mounting location is more suitable during night and non-snowy conditions. Auxiliary headlights mounted on the top of the cab or headache rack could potentially cause light bounce-back from falling snow and the snow cloud from plowing. Some operators mentioned increasing the brightness of auxiliary headlights to reduce the light bounce back from snow. Interestingly, one operator mentioned not having the problem of light bounce back after switching back to LEDs.

Bullough and Rea (1997) developed a mathematical model to predict forward visibility based on the light-source luminosity and mounting location.

$$V_f = I_{max}d \qquad \text{(Equation 1)}$$

Where, I_{max} = maximum luminous intensity (in cd) of the forward light source;

d = distance of the light source from the driver's line of sight (in m).

The calculated logarithmic (Vf) had a high correlation of r2 > 90% with the survey results of operator's comparison scores and quality ratings.

Another suggested option is to switch off the driver-side headlamp, and instead use an auxiliary headlamp to reduce the amount of back-scattered light (Rea and Thompson (2000). Some of the survey respondents also mentioned turning off the auxiliary headlights as a possible solution for the light bounce back. Additionally, shielded, louvered, or cut-off type headlamps aid in narrowing the light beam which reduces the amount back-scattered light (Rea and Thompson, 2000, Bullough and Rea, 2001). Louvered headlamps improved visibility and reduced glare compared to conventional headlamps (Bullough and Rea, 2001). Furthermore, recent manufactures are devising LED light technologies that can alter the beam output and help to reduce light bounce back during stormy condition (Information from WELDEX Corporation).

Most recent report from Lighting Research Center (LRC) tested a new lighting configuration in which the auxiliary headlights were moved up and to the right of the driver's line of the sight. This configuration was tested for two winters on NYSDOT snowplow vehicles. Operators preferred the new lighting configuration based on the improved visibility distance and reduced back-scattered from headlights (LRC, 2014).

Studies noted the concern of winter maintenance agencies of asymmetries imposed by altering the mounting positions of auxiliary headlights, on aesthetic grounds.

2.3 Impact of Color of Bulbs on Visibility during Snowy Conditions

The impact of the color of auxiliary headlamps on visibility during inclement weather conditions has been studied primarily on the basis of type of wavelength (shorter vs longer wavelength). According to Rayleigh scattering, the amount of scattering is inversely proportional to the wavelength of light. Therefore, blue light, with a shorter wavelength, will scatter more light than red light, a with larger wavelength (Bullough and Rea, 2001). Applying this same principle, yellow headlights were mandated rather than white headlights in France until 1990s. However, other studies did not find any significant advantages of using yellow or any other color lights in reducing the glare during inclement weather conditions (Boelter and Ryder, 1940, Schreuder, 1976, Moore, 1998). This is because the raindrops, snowflakes, and fine fog particles have an average diameter of 8000 nm which is greater than visible wavelength between 400 to 700 nm under which Rayleigh scattering become negligible (Rea, 2000, Bullough and Rea, 2001).

A laboratory study conducted by (Bullough and Rea, 2001) analyzed the visual performance in an aquarium tank filled with water that created "visual noise" closely mimicking snow fall. The subjective ratings showed that yellow-tinted headlamps have no significant impact on tracking performance when compared to conventional tungsten-halogen lamps, under the experimental conditions (Bullough and Rea, 2001). A significant number of survey respondents suggested using yellow fog lights to reduce the light bounce back from snow; which is consistent with older standards, but is in contrast with recent research findings.

Bullough and Rea (2001) suggest the color of headlights may have little impact on improving visibility when compared to improvements made by changing mounting location and beam width during inclement weather conditions.

Researchers at Carnegie Mellon are developing a "smart automotive headlight technology" for "seeing" through rain and snow. The idea is to have an imager that captures images illuminated by the light source and a processing unit that detects precipitation particles in the upper part of the image. It then predicts the future location of the particles and controls the light source to illuminate between particles (CMU, 2015). However, researchers did not discuss how the lighting types, such as strobe light vs steady burn light, affect this.

3. Mechanism to Prevent Snow Blowing Over the Plow onto the Windshield

Visibility for plow operators can be reduced due to light bounce back from airborne snow during plowing operations. Customized over-plow deflectors have long been used as a retrofit for reducing the “blow-over “ snow. Thompson and Nakhla (2002) conducted wind tunnel and field experiments to quantify improvement of operators visibility due to an over-plow (Figure 5). The study found that an over-plow deflector with a trap angle of less than 50° increased operator visibility by 50% from image analysis by discharging a portion of snow to the roadside and the remainder to the ground in front of the plow; resulting in the reduction of snow blowing over the plow and reaching the windshield. An engineering model further validated that an over-plow deflector should have a trap angle of less than 50° to reduce snow blowing over the plow onto the windshield (Thompson and Nakhla, 2002). A recent study developed an over-plow defelctor made up of special plastic that has low friction on its surface to minimize snow accumaltion on its surface (Figure 6). Premilinary field test results showed that over-plow deflectors are effective in keeping the front grill clear of snow as shown in Figure 7. Over-plow deflectors can also aid in keeping auxiliary headlights clear of snow if the lights are mounted lower on the truck.

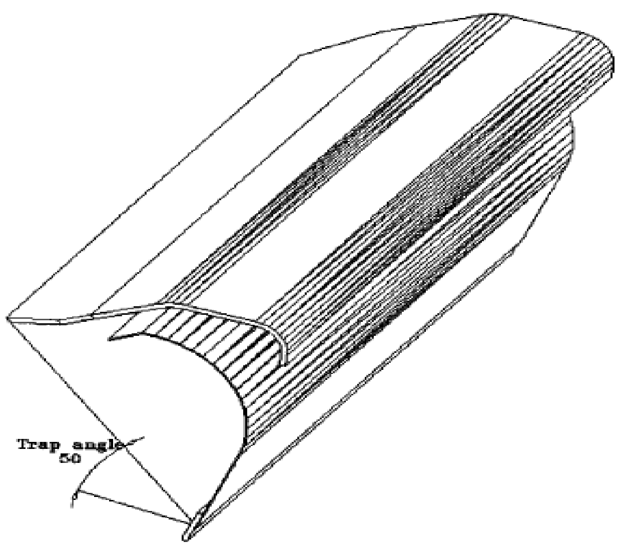

Figure 5: Fixed geometry overplow deflector used in highway trials with a trap angle of 50o (Thompson and Nakhla, 2002)

Figure 6: Over plow Deflector (NDOT, 2015)

Figure 7: Over plow deflector test run – without over plow deflector and more snow accumulation on the grill (left); with over plow deflector and less snow accumulation on the grill (right) (NDOT, 2015)

From the previous research, it can be noted that over-plow deflectors could potentially be helpful in reducing the airborne snow on the windshield. Survey respondents indicated the most commonly used mechanism to keep snow from blowing onto windshields is a set of rubber flaps on the front of the plow. Very few respondents have over-plow deflectors on their vehicles. Other methods to keep snow from blowing onto windshields used by survey respondents included air foils, bug shields, and poly plows (due to a more slippery surface).

4. Warning Lights

Warning lights typically provide increased conspicuity of the snowplow vehicle by indicating the position and direction of travel. These lights augment the identification of the snowplow vehicle provided by the regular headlights, tail lights, and side marker lights. Warning lights are typically mounted on the front, rear, and sides. Forward warning lights are typically located on the front of a vehicle such as the cab-top or bed-top. Rear warning lights are typically mounted on vertical rear surfaces of truck bodies, and provide better visibility to following traffic. Side-mount warning lights are typically surface or flush–mounted and increase visibility of the snowplow vehicle to cross-traffic and to vehicles in adjacent lanes.

4.1 Type of Warning Light bulbs

Most agencies prefer using LEDs based light systems due to the benefits such as increased reliability, increased visibility, increased conspicuity, improved efficiency, and reduced maintenance costs. This is affirmed by the survey findings that LEDs are commonly used for forward, rear and side warning light systems when compared to halogen, HID, and incandescent. A study conducted for INDOT concluded that LEDs lights are brighter in all observed conditions and different light groups (round, surface, etc.) (McCullouch and Stevens, 2008). Similarly, a study conducted in Canada recommended LEDs based lights for warning lights (Paulichuk, 2005). Another study conducted for the Minnesota DOT found that LED lights performed well, or in some cases better when viewed directly from the rear, side, or front of the snowplow vehicle when compared to standard HID strobes. However, conspicuity was reduced at off angles due to the angular intensity variation of the LED devices and due to the lenses used to increase the intensity at the front, back, and side of the snowplow vehicle (Vogt and Miller, 2008). However, this issue can be rectified by using a larger number of LEDs at different angles.

4.2 Color

The color of the light also plays a critical role in ease of visibility for the driving public. A study conducted for the Indiana DOT found that amber is the clear color preference across all color configurations followed by bright blue for warning lights (McCullouch and Stevens, 2008). Survey respondents indicated that amber and blue colored warning lights are widely used in all conditions. Interestingly, operator’s preferred white color and amber color warning lights during low visibility (e.g., fog, snow, etc.) conditions. In fact, a recent study found that lights with red, orange and yellow color components may have negative impacts during blowing snow and fog conditions. However, this study could not recommend a suitable color during low visibility conditions (Yonas and Zimmerman, 2006) NDDOT believes that white color is the most intense light to penetrate during low visibility conditions. Iowa DOT is also testing flashing blue and white LED lights on 175 snowplow vehicles and they anticipate a decrease in the number of accidents. More recently, some agencies are testing green colored warning lights in their snowplow vehicles as shown in Figure 8.

ODOT is using green flashing LED lights placed atop its snowplow vehicles. Additionally, NDDOT is currently testing steady burning - green warning lights located outside the box (along with stop/tail/turn) and on a telspar post. One of the main reasons given by NDDOT for testing green lights is the frequent use of amber lights by vehicles other than DOT trucks (oil trucks, construction trucks, etc.).

Figure 8: (The green lights demonstrated in snowy conditions on Nov. 18, 2014 (http://woodtv.com/2014/11/13/kent-co-wants-new-green-lights-for-plow-trucks/)

4.3 Intensity

Intensity of warning lights can play a key role in alerting the vehicles following behind a snowplow vehicle. In general, agencies chose the brightest light bulb type for warning lights, such as LEDs. In some cases, increased intensity could be distracting or blinding especially for other snowplow vehicle operators following behind during snow removal operations. In general survey respondents indicated warning lights can never be too bright, while a small percentage indicated that warning lights can be too bright for those following behind a snowplow vehicles. Operators who indicated warning lights can be too bright suggest having lower intensity settings especially at night. Another option suggested by operators is to keep a reasonable distance from the back of the snowplow vehicles. In general, operators who think warning lights are not too bright consider that brighter lights are better to warn drivers approaching from the rear.

4.4 Flashing patterns

Different flashing patterns improve visibility of the snowplow vehicles to nearby vehicles. The ability of a driver to detect the presence of a snowplow vehicle is different than the ability of the driver to detect the relative speed of the snowplow vehicles (perceived approach). The enhanced visibility and recognition of a slow snowplow vehicles helps to reduce the speed of the following vehicle thus preventing a collision. A study conducted for MnDOT found that low-luminance contrast created by snow clouds greatly reduces the ability of nearby drivers to detect the perceived approach to a snowplow vehicle (Yonas and Zimmerman, 2006). Additionally, flashing lights, which increase the conspicuity of snowplow vehicles, actually reduce the ability of drivers to accurately perceive an approaching snowplow vehicle. The study recommends developing lighting techniques that increase the luminance contrast of rear lighting to help following drivers improve the perceived approach to a snowplow vehicle. The study also suggests using only steady burning lights if agencies choose only one lighting system. Both flashing lights and steady burning can be used if they are spaced sufficiently apart to improve conspicuity of the snowplow vehicle. Further, flashing lights should not be excessively brighter than steady burning lights (Yonas and Zimmerman, 2006). Interestingly, survey responses are in contrast with the research findings; operators believe that flashing lights help following drivers estimate the relative speed of the snowplow vehicles. Additionally, the survey also found that steady burning lights are not commonly used as rear warning lights.

4.5 Amperage requirements for various lighting packages

Incandescent bulbs have been used for headlamp and taillight systems for over a century since the advent of the automobile. In the last two decades automobiles and trucks increasingly use halogen, high-intensity discharge (HID) and light-emitting diode (LED) as light sources.

Incandescent light bulbs work on the principle of producing light by passing an electric current through a wire (tungsten) filament which super heats until it glows. A halogen bulb is an incandescent lamp with the addition of small amount of a halogen such as iodine or bromine inside the bulb capsule. Incandescent and halogen bulbs generally require more energy as most of the energy is released in the form of heat. High-intensity discharge bulbs produce light by creating an arc between two electrodes in a quartz-glass or fused alumina tube. HID lamps require a substantial amount of power during start-up to create the light, but then less power to sustain the created light. A light-emitting diode is composed of two-lead semiconductors (P-type semiconductors and N-type semiconductors), which emits light when a suitable voltage is applied to the leads. LEDs are very efficient is converting electricity in to light and also produce less heat. Overall, LEDs consume less power when compared to HIDs, halogen, and Incandescent bulbs.

A comparison of the amperage requirement of halogen, HID and LED light source is reported below. A halogen bulb rated at 150 watts draws a battery current of about 12.5 amps. However, a 35 watt HID light only requires 3 amps of current and a LED requires about 2-3 amps (www.fourwheeler.com). A study conducted for MnDOT found that instantaneous and average power used by all LEDs fixtures are significantly lower than standard strobes (HID). The study compared the standard strobe (HID) with three LED bulbs shown in Table 1 (Vogt and Miller, 2008).

Table 1: Electrical Characteristics of the tested strobes (Vogt and Miller, 2008)

Fixture description	Peak current (Amps)	Peak power (Watts)	Energy/cycle (Joules)	Average power (Watts)	Duty cycle (%)	Cycle time (sec)
Standard strobe	11.3	137.3	49.6	58.2	>0.7	0.82
Whelen LED	3.1	38.1	10.8	13.1	35	0.82
PSE 257 LED	5.9	73.0	37.4	41.9	58	0.89
Federal LED	3.8	46.0	46.0	15.9	25	2.90

The same study found that conspicuity was reduced at off angles for LEDs when compared to HID strobes (Vogt and Miller, 2008) which would mean that more LEDs are required at different angles to achieve the same conspicuity as other bulb types. In addition, LEDs may require heated lens to stay clear of snow during snowy conditions and heated lens would require additional amperage. Amperage requirements for having additional lights and heated lens should be also considered when using LEDs. However, LEDs may compensate for these draw backs with the efficient and reliable design, especially for snowplows operating in harsh environments.

In recent years as snowplow vehicles have added more devices and equipment that consume more electrical power, older, lower-amp alternators have had to be replaced with higher capacity units. Likewise, newly purchased vehicles are usually ordered with the higher capacity alternators. As there is a continuing trend towards installing more warning and work lights on snowplow vehicles, selection of energy-efficient lighting systems will help reduce or at least contain the "amp-up." Within the next 5-10 years even more operational and communicative devices and systems will be added to the trucks putting additional demand on the electrical generating capability. These devices and systems will be for virtual guidance and interconnectivity (the connected/automated vehicle concept). Already trucks in some agencies have more of a "cockpit" look with electronic controls for plows, spreaders and liquids applicators, AVL, GPS, two-way radio, cell-phone (IADOT), computers, and CCTV in addition to standard controls for general vehicle operation. This is a problem challenging police, fire and ambulance agencies as well.

4.6 Mounting locations for warning lights

For survey findings, forward warning lights are commonly mounted and extended above the cab and truck bed with 360 degrees visibility with single beacon and multiple lamps. Very few respondents have forward warning lights that are not partially or completely visible from the rear. Therefore, it is clear that agencies are trying to mount the forward warning lights to achieve complete visibility from the rear and sides. .

For rear warning lights, survey respondents commonly use flush mounted, followed by pole or telespar mounted lights, single or multiple beacons and surface mounted lights. Elevating the rear warning lights (pole mounted or telespar mounted) is becoming more popular with survey respondents. NDDOT recommends elevating rear warning lights for increasing air flow around lights and reducing the snow accumulation. Figure 9 shows a picture of rear warning lights located on telespar and snow accumulation. It can be noted that there is plenty of snow on the back of the box and there is no snow accumulation on warning lights located on telespar. However, operators must be careful during loading and unloading operations to avoid damaging the elevated lights. In addition, NDDOT has also designed brackets for the lights during summer.

Figure 9: Rear warning lights mounted on the telespar and snow accumulation

As explained in the previous section, steady-burn (constant burn) warning lights play a key role for drivers to detect the relative speed of the snowplow vehicle (perceived approach). Furthermore, flashing lights help drivers detect the presence of a snowplow vehicle. It is therefore important to have different mounting locations for steady-burn lights to differentiate from flashing/strobing warning lights. Yonas and Zimmerman (2006) suggested mounting steady burning lights on either side of the rear end of the snowplow vehicles such that they are spaced apart and do not interfere with flashing warning lights.

Based on the previous findings, we proposed a mounting location for steady burn and flashing lights considering the following vehicle driver's line of sight as shown in Figure 10. The proposed mounting location assumes that at a longer viewing distance, the following vehicle driver will have a full view of the back of the snowplow vehicle ahead; and at shorter viewing distance, the following driver will have a limited view of the back of the snow-plow vehicle ahead as show in Figure 10.

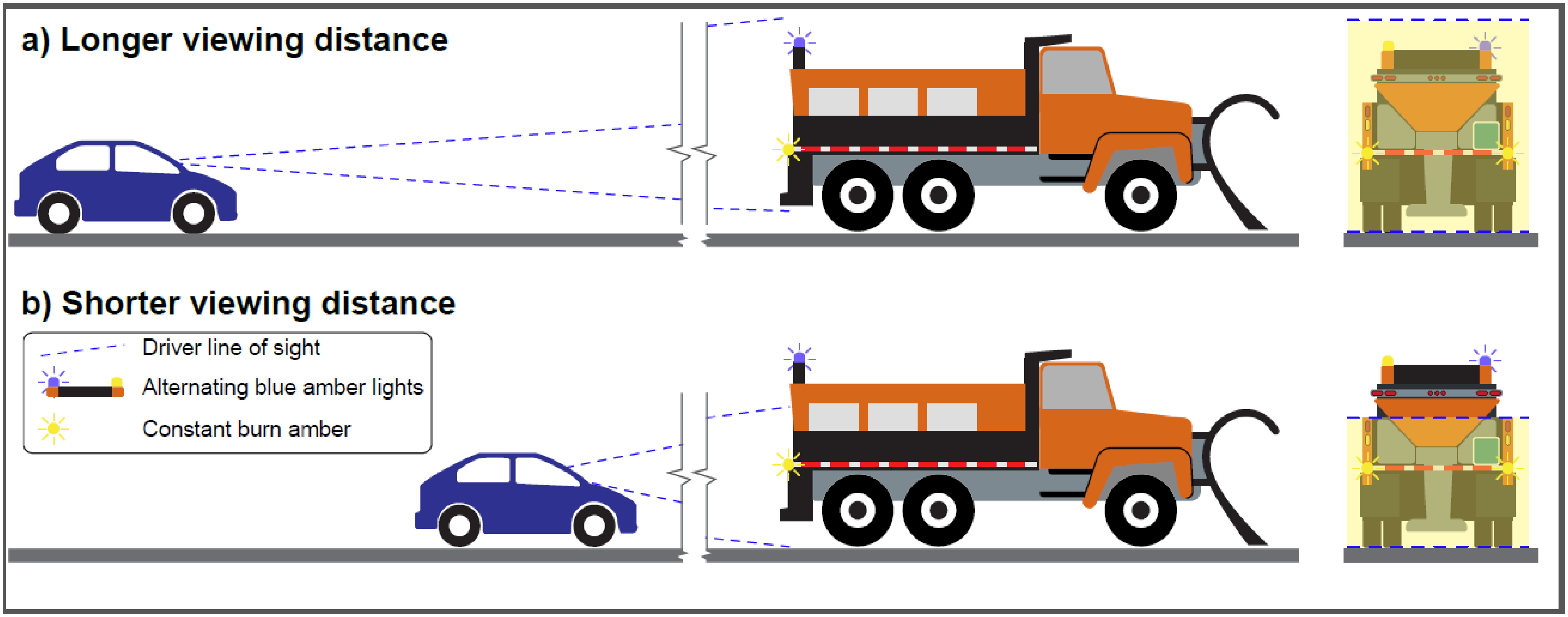

Figure 10: Proposed mounting location for flashing and steady burning lights

Mounting the flashing lights on the top of the truck bed will help drivers of other vehicles identify the snow-plow vehicles from a farther distance. As they get closer to the snow-plow vehicle, the flashing lights will not be visible (not in their line of sight) and the steady burn lights will become more visible and help the following driver to gauge the relative speed of the snowplow vehicles perceived approach. It is also important to have a reasonable distance between lights when using multiple colors for rear warning lights. One survey respondent mentioned that having different color lights closer together will appear as a single light when viewed from rear. It should be noted that already existing steady burning marker lights may help to estimate the relative speed of plow if they are brighter than flashing lights and mounted at a reasonable height (such that it is visible for drivers following the plow from a reasonable distance).

5. Work Lights

Work lights are floodlights or spotlights mounted at various places on the truck exterior for illumination of specific locations such as a wing-plow, under-body plow, top of a truck bed, spreader-spinner, cab-steps, etc. Work lights enhance the safety and convenience for the truck operator. Typical mounting locations of work lights identified by survey respondents are the side and rear of the vehicles. Very few respondents have their work lights located on the front of the vehicle. The most commonly used type of work light by survey respondents are spot and flood lights. LEDs and halogen bulbs are the most commonly used light bulb for work lights. The white color is used by the majority of survey respondents with a few operators indicating they use amber, blue, and amber-white color for their vehicle work lights. Respondents indicated they prefer additional work lights on tow plows, wing plows, top of the cab, under body lights, top of sanders (to keep track of materials), and some additional flood lights on the rear.

6. Mechanism to Keep Lights Clear of Snow

One of the major safety issues with warning lights and work lights is that they become covered with a layer of snow and are no longer visible. LEDs are becoming more popular among winter maintenance agencies for warning lights but they do not produce enough heat to melt snow off the surface of the lights, whereas halogen, incandescent, and HID bulbs do. A recent study found that LEDs accumulate more snow on light surface compared to standard strobes (Figure 11). It is therefore important to keep the lights clear of snow in order to keep the snowplow vehicles visible during snowy conditions.

Figure 11: Comparison between standard strobe and Whelen LED after heavy snow conditions (Vogt and Miller, 2008).

Based on a survey conducted in Canada, a wind deflector mounted above the dump body of the snowplow was recommended to keep the rear warning lights free from snow build-up. The study mentioned that wind deflectors can become clogged with snow (Paulichuk, 2005). Nevada DOT designed and installed rear airfoils on class 15 truck and found them to be very effective in keeping the rear of the truck clear of snow as shown in Figure 12 (NDOT, 2015). Research conducted for MnDOT also found air foils to be effective in keeping the rear of vehicles clear of snow and found they eliminated the time required by operators to clean off the snow (MnDOT, 2015). Iowa DOT recommended the use of "scoop" tailgate deflectors to decrease the amount of snow on the back of vehicles (Kamyab et al., 2002). Additionally, Iowa DOT also recommended installing air blasters (controlled by operators, to clear snow from the lights) on trucks operating on interstates and four-lane roadways (Kamyab et al., 2002) . However, wind deflectors may not be effective for tail lights and brake lights that are located at the bottom truck box. From the survey, few agencies mentioned having wind deflectors, air puffers, mini-foils over individual lights, or air foils to decrease the amount of snow on the back of vehicles. However, one survey respondent mentioned having wind deflector. Initial studies show the technology works, but may require additional engineering before being fully implemented by winter maintenance agencies.

Figure 12: Airfoil test run – without airfoil and more snow accumulation on the rear (left); with airfoil and more snow accumulation on the rear (right) (Nevada DOT, 2015).

Another new emerging technology is the use of heated lens to keep the lights clear of snow. Nevada DOT suggested the feasibility of thin sheet heaters powered by a 12 volt source to be used on snowplow lights (Nevada DOT, 2015). North Dakota DOT (NDDOT) mentioned using heated lens on some of its trucks. However, it is important to have a control switch that can turn on and off based on the conditions. During warm snow events (around 25°F or warmer) snow generally sticks on the lights and heated lens helps to melt the accumulated snow on the lens. However, in cold snow events (around 15°F) snow will likely not stick on light lens, in such cases, using heated lens can actually create a dome of ice over the LED lens. Heated lens are rarely used by winter maintenance agencies as was indicated by the survey responses.

It is also possible to keep the lights clear of snow by altering its mounting locations such that air flow is enhanced around the lights. Some agencies and operators mentioned moving tail and brake lights onto the side of the side of the vehicle in winter to allow the wind to clear the snow. NDDOT suggests using telespar mounted warning lights elevated above the back of the vehicle. One agency responded using spraying with Deluxe Shine or Rain-x on the light surface. Iowa DOT investigated using Teflon spray on light surfaces and found that it was not effective.

7. Retro-Reflective Markings

Retro-reflective markings are typically added on the rear of the vehicle and side of trucks. Retro-reflective markings increase conspicuity of the vehicle at night and during low-light conditions. A study conducted in Canada, recommended using two strips of reflective tape on the back of the snowplow vehicle which will be illuminated by approaching vehicles (Paulichuk, 2005). Another study conducted by Texas Transportation Institute found that retro-reflective magnetic strips improve the conspicuity during nighttime operations when used on flagger vehicles (Fontaine et al., 2000). However, retro-reflective materials become completely ineffective if covered by snow. Similar complaints were raised by survey respondents, with the biggest concern being keeping the reflective markings 100% clean which becomes difficult resulting in reduced effectiveness. The most commonly used color combinations for reflective markings are red and white. Some of the other color combinations reported by respondents include orange and white, red-white-yellow, black and yellow, and red-white-blue. Retro-reflective markings are commonly used on the rear of the vehicle, and less commonly on the sides.

8. Day versus Night Settings

In general, snowplow vehicles more frequently have warning lights to improve conspicuity, than standard maintenance equipment (Kamyab et al., 2002). Some agencies prefer brighter light sources for warning lights. Unfortunately, the combination of more light sources and higher intensities may temporarily blind approaching vehicle drivers especially during nighttime operations. Gibbons et al. (2008) found that the effective-intensity light source used in the daytime to provide adequate daytime conspicuity will cause significant glare for opposing drivers at night. It is therefore important to maintain an effective intensity light source with respect to day-versus-night settings (Gibbons et al., 2008). A study conducted by Michigan Transportation Research Institute recommended using different intensity lighting for daytime and nighttime operations. Intensities can be reduced either manually or automatically (Flannagan et al., 2008). Photocells have been previously used by agencies in flashing arrow boards to automatically dim (minimum 50% dimming) the lights during night time operations (Maintenance Manual, 2002). Survey respondents indicated that day-versus-night time settings are not a commonly available feature in snowplow vehicles. Very few respondents mentioned having day-versus-night light settings on their vehicles, and those that do require the operator to manually switch between day and night settings. One agency indicated it has a few vehicles with automatic settings to change between day and night light settings.

9. Conclusions

Based on the information gathered from the literature search, agency survey, and operator survey, the following conclusions and recommendations are made regarding equipment lighting for snowplow vehicles.

- Halogen bulbs followed by LED bulbs are the most commonly used bulb types for auxiliary headlights. LEDs are favored for use in new vehicles, retrofits, and replacements due to improved visibility.
- Mounting the auxiliary headlights away from operator’s line of sight with narrow beams (spot light) helps to reduce the light bounce-back during adverse weather conditions. In particular, mounting auxiliary headlights at the lowest possible location (above the plow or fender walls) is recommended.
- Yellow or other color auxiliary headlights may not have an impact in reducing the amount of back-scattered light.
- With the emergence of LEDs for auxiliary headlights, warning lights and work lights, it is important to have some mechanism to keep the lights clear of snow because LEDs do not produce enough heat to melt snow and ice off the light surface.
- Over- plow deflectors have been found to be effective in keeping the front grill clear of snow, especially if auxiliary headlights are mounted at the lowest possible location on the vehicle (above the plow or fender walls).
- Amber is the color most commonly used for warning lights. However, agencies are using and/or testing blue, white, and green colors. Operators prefer white colored warning lights because of perceived increased conspicuity during low visibility (e.g., fog, storm conditions, etc.) conditions.
- It is important to have both flashing lights and steady burning (constant burn) lights that are spaced apart for rear warning lights. Flashing lights helps to identify the presence of a plow and steady burn lights aid in the estimation of the relative speed of plow.
- Retro-reflective tape markings are very effective and provide an additional level of warning for approaching vehicles. However, keeping retro-reflective markings clear of snow and visible at all times is an issue during snow plowing operations.
- A combination of wind deflectors and heated lens can be used to keep the warning lights and retro-reflective tape clear of snow. However, it is important to have a control switch that can turn on and off the heated lens based on the conditions.
- The issue of increased brightness introduced by warning lights can be resolved by using day-versus-night settings for lights on snowplow vehicles, but this feature is not commonly available.

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Appendix A

Summary of Agency Survey Responses

A total of 58 respondents participated in the survey representing from 26 states within the U.S. Survey responses were from state/province DOT (83%), county Public Works/DOT (3.8%), and municipal public works (9.4%). Other respondents groups included retired and international airport/highway/toll road personnel.

Fleet Information

Single-axle trucks, tandem-axle trucks, 1 ton trucks, ½ and ¾ trucks, graders, and front-end loaders are the commonly used by agencies for winter maintenance activities. In terms of plow configuration, 1 ton trucks, ½ and ¾ ton trucks, and front-end loaders commonly have front plow configurations. Single axle trucks commonly have both front and right wing plow configurations. Tandem axle trucks are most commonly equipped with the following plow configurations - front plow, right wing plow, left wing plow, underbody plow, tow plow, and V-plow. Blower attachments are commonly used on front-end loaders and tractors. For fleet size, most responding agencies generally have fleet size of less than 50 for all types of truck configurations. However, single axle trucks, tandem-axle trucks, ½ and ¾ ton trucks, and front-end loaders generally have fleet size of more than 100. It should be noted that single and tandem-axle trucks were indicated as being used by all responding agencies, while triple-axle trucks are not commonly used among responding agencies.

Auxiliary Headlights

Auxiliary Headlights are typically used on the front of plow trucks and provide supplemental illumination of the road surface during plowing. They also provide forward-lighting and directional signals when a raised plow obscures standard truck headlights. From the survey responses, the most commonly used bulb type for auxiliary headlights is halogen bulbs (79.2%) followed by *light-emitting diode* (LED) light bulbs (47.9%). In contrast, very few responding agencies use incandescent light bulbs (20.8%) and *high-intensity discharge* (HID) bulbs (4.2%) for auxiliary headlights. Even though the halogen bulbs are commonly used for auxiliary headlights, respondents mentioned that their agencies are currently specifying LEDs for their new trucks. For older trucks, some agencies are replacing their current bulbs with LEDs. Noticeably, one agency after receiving positive feedback from the field has elected to retrofit LEDs for their older trucks. Some of the LED lights used by agencies include Whelen Micro Pioneer lights, Truck-Lite 80880, and Truck lite 80888.

- Halogen bulbs followed by LED bulbs are the most commonly used bulb types for auxiliary headlights.
- LEDs are favored for use in new vehicles, retrofits, and replacements.

Within auxiliary headlights, most agencies use twin single with the turn signal/parking light configuration (78.7%), compared to twin dual with the turn signal/parking light configuration. Some agencies also use single dual without the turn signal/parking light configuration.

The most common location for mounting the auxiliary headlights reported responding agencies was on the truck body (59.6%), followed by the plow frame (34%), and the cab hood (27.7%). One agency uses "h" brace style bracket bolted to the outside of the grille with adjustable heights for mounting auxiliary headlights.

One of the main concerns with snowplows is the light bounce-back from auxiliary headlights during adverse weather conditions. The majority of respondents reduce the light bounce-back by altering the mounting position (13 responses) of auxiliary headlight such that it is away from the driver's line of sight. In addition, respondents also use yellow fog lights (11 responses), turn off the auxiliary headlamp that is in driver's line of sight (10 responses), and turn off the cab roof spot light (3 responses) to reduce the amount of back-scattered light. It is should be noted that some agencies (6 responses) do not have any adaptions to deal with this light bounce-back. Some of the other practices used by the agencies include:

- Turning off the truck lights and use only the auxiliary headlights.
- Auxiliary headlamps with horizontal optics and reduced vertical beam.
- Use small hoods over the round headlights.
- Mounting auxiliary lights at the lowest point which is above fender wells.
- Mount spot lights directly beside plow lights.

One respondent noticed no complaints about light bounce-back after switching to LED lights. However, the same respondent is unsure if the intensity of the LED bulbs played a role in reducing light bounce-back.

In order to keep the snow from blowing onto the windshield more than half of the respondents (55.6%) used some kind of mechanism such as rubber flaps (8 – 15 inches), over plow deflectors, bug shield, air foils, wind deflectors, and rubber belting over the front of flow. In contrast, 44.4% of respondents do not use any kind of mechanism to keep the snow from blowing onto the windshield.

Warning Lights

Warning lights typically provide increased conspicuity of the plow vehicle; aiding in indication of position and direction of travel of the plow vehicle. These lights augment the identification of the plow vehicle provided by the regular headlights, tail lights, and side marker lights.

1. Forward Warning Lights

Forward warning lights are typically located on the front of a vehicle such as the cab-top or bed-top. The most commonly used type of from respondents is 'twin beacon' light (26 responses). In addition, responding also use forward warning lights such as ‘single light bar, mid-full size’ (16 responses), and a light head (mounted in multiple locations above the cab shield) (16 responses). Single beacon (12 responses) had the least number of responses for forward warning light. Within the forward warning light, ‘strobe’ warning light pattern (45 responses) was commonly used by respondents, followed by flashing (27 responses), and rotating (25 responses) warning light patterns. As expected, steady-burn light (3 responses) was not commonly used for forward warning lights. It should be also noted that one respondent mentioned switching from using three beacons to using light bars.

The most common mounting location and grouping for forward warning lights used by responding agencies is mounted them above the cab and truck bed such that they have partially or 360 degree visibility from rear of vehicle. Responding agencies also have their forward warning lights mounted above the cab and truck bed with 360 degree visibility for single beacon (38.9%) and light bar (27.2%) with multiple lamps. About 25% of responding agencies use a pair of beacons mounted on top of cab placed outboard which are partially visible from rear. In contrast, very few agencies have their forward warning lights mounted on top of cab, such that they are not visible from rear for both single beacons and multiple lamps (9.1%). Likewise, only few responding agencies have their forward warning lights mounted above the rear-view mirrors (9.1%).

All amber LEDs are commonly used for warning lights on the front, rear, and side vehicles, with strobe and flashing light patterns.

Commonly used bulb types in forward warning lights were LEDs, regardless of the type of forward warning light based, whether standard for new vehicles or retrofitting older vehicles. Some agencies also use halogen and HID bulbs for forward warning lights. As expected no agency uses incandescent bulbs for forward warning lights. The most commonly used color of forward warning lights by survey respondents are all-amber (70.5%). In addition, some agencies use amber-white (20.5%), and amber-blue (15.9%) combinations. One responding agency uses the combination of amber-white –blue for forward warning light.

2. Rear Warning Lights

Rear warning lights are typically mounted on vertical rear surfaces of truck bodies, and provide better visibility to following traffic. Types of rear warning lights include surface, flush-mount, and beacons. Side-mount warning lights are typically surface or flush–mounted and increase visibility of the truck to cross-traffic and to vehicles in adjacent lanes. The most common rear warning lights are flush mounted (28 responses), and surface mounted lights (20 responses). However, in comparison some agencies use single or multiple beacons (10 responses), pole mounted lights (7 responses), light bars (8 responses), and swivel mounted (7 responses) rear warning lights. Some of the other mounts include light mounted in bed corners (left and right), and rear facing warning on wing ends. Additionally, most agencies use strobe and flashing lights for rear warning lights. Rotating and Steady burn are used by very few agencies for rear warning lights.

The most commonly used bulb type for side warning lights are LEDs, followed by halogen, HID, and incandescent. In particular, LEDs are most commonly used for flush and side mounted lights. The most commonly color of rear warning lights are the all-amber color (61%). Some responding agencies use amber-blue (26.8%), amber-white (17.1%), and amber-red (4.9%) combinations for rear warning lights. One responding agency uses all-red for rear warning lights.

3. Side Warning Lights

Side-mount warning lights are typically surface or flush–mounted and increase visibility of the truck to cross-traffic and to vehicles in adjacent lanes.

The most commonly used side warning lights by survey respondents are flush mounted (18 responses) and surface mounted lights (21 responses). Very few agencies use single or multiple beacons (6 responses) for their side warning lights. Some respondents indicated not having warning lights in the side of the vehicle. The most commonly used side warning light patterns are the flashing, followed by steady-burn, and strobe lights. None of the agency uses rotating lights for rear warning lights. The most commonly used bulb type for side warning lights used by responding agencies are LEDs, followed by halogen, HID, and incandescent. In particular, LEDs are most commonly used for flush and side mounted warning lights. The most commonly used color of side warning lights are all-amber color (69.4%), with some agencies using amber-white (16.7%), amber-red (16.7%), and amber-blue (2.8%), and various other combinations.

4. Devices/mechanisms to increase of effectiveness of warning lights

The driving public generally drives at higher speeds than snow plow vehicles during plowing operations. It has been reported that rear end accidents often occur due to the inability of the following driver to estimate the speed of the snow plow. Lighting types can be selected to help the following drivers better estimate the speed of snow plows. Based on survey responses preferred lighting patterns for estimating snow plow speed are flashing; alternating (i.e. "wig-wag") (61.3%). Very few respondents prefer flashing; random sequences (22.6%) and flashing; all at same time (such as hazard flashers) (12.9%) type of warning light for estimating snow plow speed. Only a few respondents indicated they preferred steady burning warning lights to estimate the relative speed of the snow plow to following vehicles.

Another issue introduced by warning lights is increased brightness, especially for plow truck drivers following behind another truck during train-type (or tandem) snow removal operations. The following techniques have been used by responding agencies to accommodate the increased brightness introduced by warning lights:

- Settings inside the truck can be used to reduce intensity of warning lights (dimming adjustment) especially for night time operations.

- Mounting the strobing/flashing warning lights above or below the driver's line of sight.
- Shut off the warning lights.
- Slowing down the flashing patterns.
- Plow trucks drop back or spread out if the drivers are getting blinded.

Of the five technique mentioned above, settings to reduce intensity of warning lights was the commonly used technique (9 respondents). Some respondents do not have any accommodation currently to resolve this issue. Also, a few agencies reported not having the issue of increased brightness as they generally plow using a single truck.

Further survey analysis revealed that nearly 70% of the respondents do not have a day versus night settings of lighting in their agency vehicles. Only about 15% of responding agencies have day versus night settings in their vehicles. The day versus night lighting settings in their vehicles are all manually operated except for one agency that has a few vehicles with automatic settings to change between day and night.

> The issue of increased brightness introduced by warning lights can be resolved by using day versus night settings for lights on snow plows, but this feature is not commonly available.

Another issue reported with warning lights is snow sticking on light surface during adverse weather conditions. Survey respondents indicated that more than 50% of the respondents (18 responses) do not have any devices or mechanism to keep lights clear of the snow. A few agencies (4 responses) are either in testing or the planning phase to install some kind of device or mechanism to reduce snow sticking on the light surface. Below are some of the techniques which are currently used by the responding agencies to keep lights clear of the snow:

- Air foils to keep rear lights clear of snow.
- Mini-foils over individual lights.
- Wind and snow deflectors.
- Air puffers.
- Move tail and brake lights onto the side of the truck bed in winter to allow the wind to clear the snow.
- Spray with Delux shine or Rain-x on the light surface.
- Telespar mounted warning lights are used to keep air flowing around the strobes.
- Heated lenses.

Work Lights

Work lights are floodlights or spotlights mounted at various places on the truck exterior for illumination of specific locations such as a wing-plow, under-body plow, top of a truck bed, spreader-spinner, cab-steps, etc. Work lights enhance safety and convenience for the truck operator. Typical mounting locations of work lights identified by survey respondents are the side and rear of the vehicles. Very few respondents have their work lights located on the front of the vehicle. The most commonly used type of work light by survey respondents are spot and flood lights. LEDs (59.5%) are the most commonly used light bulb for work lights followed by Halogen bulbs (42.9%). Very few responding agencies use incandescent and HID bulbs for work lights. Some of the bulb used in work light include 4414 and Trucklite #8160 LED. The most commonly used color of work lights used by responding agencies is white color (92.5%). Few responding agencies indicated using amber color for work lights at the rear of the vehicle.

> Work lights are most commonly located on the side and rear of vehicle, and use LED and halogen bulbs.

Retro-reflective markings

Retro-reflective markings are typically added on the rear of the vehicle and side of trucks. Retro-reflective markings increase visibility of the vehicle at night and during low-light conditions. Survey responses indicate that 85% of the responding agencies use some sort of the retro-reflective materials on their snowplows, while only 10% of the responding agencies do not use retro-reflective materials. The most commonly used color combinations used by responding agencies are the 'red and white' (25 responses), and very few agencies use orange and white (4 responses) combinations for reflective markings. Some of the other combinations include 'red-white-orange', 'black and orange', 'red-white-blue', and 'blue only'. Typical patterns of retro-reflective markings used by survey respondents include reflective markings on the body outline (rectangle) (56.8%), followed by chevrons (37.8%), horizontal stripes only (27%), and vertical stripes only (16.2%).

> Red and white retro-reflective markings are the most commonly used among responding agencies. Keeping retro-reflective markings clear of snow and visible is an issue during snow plowing operations.

Responding agencies indicated they remove sticking snow from the reflective markings surface manually by operator either during re-loading material or re-fueling. Some agencies also mentioned cleaning periodically without any effective schedule. It should be also noted that none of the agencies have any automatic devices or mechanism to remove the snow sticking on the retro-reflective markings.

Appendix B

Summary of Operator Survey Responses

A total of 369 respondents participated in the survey. The following section provides a summary of the survey results. Survey responses were provided from state/province DOT (97.1%), county Public Works/DOT (0.9%), and municipal public works (2.3%) agencies. Other responding groups include airport authority and private contractors. The survey respondents are from California, Colorado, Massachusetts, Michigan, Missouri, Nebraska, North Dakota, Oregon, South Dakota, Vermont, and Virginia.

The majority of the operators who participated in the survey commonly operated single-axle trucks, tandem-axle trucks, 1 ton trucks, ½ and ¾ trucks, graders, front-end loaders and tractors. In terms of plow configuration, most operators have a front and right wing plow configuration on their vehicles followed by underbody plow, v-plow, and left wing plow. A few respondents indicated they have a tow plow, blower attachment, or sweeper on their vehicles.

Auxiliary Headlights

Auxiliary Headlights are typically used on the front of plow trucks and provide supplemental illumination of the road surface during plowing. They also provide forward-lighting and directional signals when a raised plow obscures standard truck headlights. From the survey responses, it can be noted that approximately 80% of the respondents have halogen bulbs in their vehicle for auxiliary headlights followed by LEDs (11.6%) and Incandescent bulbs (9.6%). Less than 1% of the respondents reported having HID bulbs in their vehicle. This shows that halogen bulbs are commonly used for auxiliary headlights. Some respondents also mentioned testing LEDs in some of their vehicles.

Within auxiliary headlights, most operators use twin single with the turn signal/parking light configuration (77.8%), compared to twin dual with the turn signal/parking light configuration (15.0%). Some operators also use single dual without the turn signal/parking light configuration (11.9%).

For the effectiveness of auxiliary headlights, responding operators rated the auxiliary headlights as Excellent (3.9%), Very Good (13.9%), Good (36.0%), Fair (31.7%), and Poor (14.5%). Analysis indicates that operators using halogen bulb had mixed opinions about the performance of auxiliary lights. However, respondents using LEDs generally viewed performance positively. In contrast, respondents using incandescent bulbs in their vehicles viewed their performance as poor. It should be also noted that two respondents using HID bulbs viewed their performance positively.

The most common location used for mounting auxiliary headlights is on the truck body (75%), followed by on the cab hood (23.2%), and plow frame (17.4%). In addition, some respondents also mentioned having auxiliary lights on the top of the front fenders, on the grill, and on top of headache rack. In general, most operators (82.1%) stated that they are satisfied with the mounting location of the auxiliary headlights, while less than 10% of the respondents were not happy with the mounting location.

> In order to resolve the issue of back-scattered light, operators are generally looking to move the auxiliary headlights away from their line of sight (top, low, and side) while increasing its brightness

Light bounce-back during adverse weather conditions has been identified a concern for snowplow operators. Most of the responding operators face the problem of back-scattered light at least sometimes during plowing operations. In particular, respondents mentioned having the problem of back-scattered light during heavy snow and during high wind conditions. A smaller number of respondents (21.3%) do not face the problem of back-scattered light. In order to rectify the problem of back-scattered light, operators suggested the following changes:

- The brightness of auxiliary lights can be increased by installing LEDs.
- Yellow fog lights can be mounted lower on the plow with a separate control switch.
- Lights can be mounted on the top corners of the plow.
- Lights can be mounted higher on the truck such as the top of the cab.
- Lights can be mounted at the lowest possible place that is above the plow.
- Use black paints on the back of plow and hood to reduce glare.
- Switch between cab lights and hood lights to increase visibility.

It can be noted that operators are generally looking to move the auxiliary headlights away from their line of sight (top, low, and side) while also increasing the brightness of auxiliary headlights.

To keep the snow from blowing onto the windshield, 32.8% of respondents have some sort of mechanism to keep the snow from blowing on to the windshield, while 67.7% of respondents do not have any mechanism to keep the snow from blowing on to the windshield. Some of the mechanisms used include:

- Rubber flaps on the front of the plow (more commonly used),
- Over plow deflectors,
- Air foils,
- Bug shields,
- Poly plows.

Warning Lights

Warning lights typically provide increased conspicuity of the plow vehicle; aiding in indication of position and direction of travel of the plow vehicle. These lights augment the identification of the plow vehicle provided by the regular headlights, tail lights, and side marker lights.

Forward Warning Lights

Forward warning lights are typically located on the front of a vehicle such as the cab-top or bed-top. The most commonly used type of forward warning lights by respondents was the twin beacon (149 responses), followed by the single beacon (106 responses), light head (93 responses), and single light bar mid-full size (35 responses). The lighting pattern most commonly used with forward warning lights is the strobe warning light (317 responses), followed by flashing (69 responses), rotating (53 responses), and steady-burn (2 responses). One respondent mentioned using flashing LED lights mounted on the top corners of truck box extended on telespar posts about 12 to 18 inches above sander grates. Additionally, some operators mentioned using three single mounted strobes (blue, white, and amber).

Operators most commonly have their forward warning lights mounted and extended above the cab and truck bed with 360 degrees visibility for single beacon (43.2%), and multiple lamps (38.2%). Very few respondents have forward warning lights that are not visible from the rear for both single (7.6%) and multiple lamps (includes light bar) (4.1%). About 13% of respondents have a pair of beacons mounted on top of the cab placed outboard which are partially visible from the rear. Additionally, few respondents have their forward warning lights mounted above the rear-view mirrors (3.8%).

For forward warning lights most operators use LEDs irrespective of the type of forward warning light (166 responses), followed by halogen (121 responses), HID bulbs (49 responses), and incandescent bulbs (36 responses).

The most commonly used color of forward warning lights by respondents is all-amber color (59.3%), followed by amber-blue (30.6%), amber-white (14.8%), all-blue (5%), all-white (3.8%) and blue-white (1.4%) combinations. Some operators also mentioned using the combination of amber-white–blue for forward warning light. One operator mentioned testing green for their forward warning lights and another is testing white light during snow fall.

Rear Warning Lights

Rear warning lights are typically mounted on vertical rear surfaces of truck bodies, and provide better visibility to following traffic. Types of rear warning lights include surface, flush-mount, and beacons. Side-mount warning lights are typically surface or flush–mounted and increase visibility of the truck to cross-traffic and to vehicles in adjacent lanes.

The most commonly used rear warning lights by respondents are flush mounted (137 responses), followed by pole mounted lights (107 responses), single or multiple beacons (84 responses) and surface mounted lights (77 responses). Light bar (18 responses) and swivel mount (14 responses) rear warning lights are used as well but less frequently. Most respondents use strobe and flashing light patterns for rear warning lights. Rotating and steady burn patterns are used by a few operators for rear warning lights.

All-amber color (39.2%), amber-white (27.7%) and amber-blue (309%) are most commonly used by operators in their vehicles for rear warnings lights. Some operators also use all-blue (4.5%) and all-white (2.2%) for their rear warning lights. A few respondents indicated they use the following combinations amber-red, amber-green, amber-green, white-red combinations for rear warning lights. One respondent uses amber-blue and optional white in foggy conditions for the rear warning light. The most commonly used bulb types for rear warning lights are LEDs followed by halogen, HID, and incandescent bulbs.

> Operator's preference of white color warning lights increases during low visibility (e.g., fog, storm conditions, etc.) conditions.

Side Warning Lights

Side-mount warning lights are typically surface or flush–mounted and increase visibility of the truck to cross-traffic and to vehicles in adjacent lanes.

Almost equal responses were received for flush mounted (63 responses), surface mounted lights (69 responses), and single or multiple beacons (57 responses) as their vehicles side warning lights. The most commonly used side warning light patterns are strobe, followed by flashing, and steady-burn lights. A few respondents have rotating lights for side warning lights.

The most commonly used bulb type for side warning lights are LEDs followed by halogen, HID, and incandescent. In particular, LEDs are most commonly used for flush and side mounted warning lights. For color, all-amber (58.3%) was most commonly used by operators for side warnings lights followed amber-blue (14.7%). A few operators indicated they use amber-white, amber-red, amber-green, all-blue, all-white, and all-red as combinations for side warning lights.

Devices/mechanisms to increase of effectiveness of warning lights

The color of warning lights plays a key role in warning drivers. Additionally, the required light color and intensity may also change based on the background light condition (day, night, and low visibility conditions). Survey respondent's preference of amber and blue color diminishes during low visibility conditions when compared to daytime and nighttime conditions. In contrast, preference of white color increases during low visibility conditions when compared to daytime and nighttime conditions. This shows that some operators prefer white color during low visibility conditions. It was also found that operators prefer flashing LED lights (57.7%) and flashing strobe warning lights (37%) to identify the presence of the snow plow vehicle from the rear. Almost none of the respondents prefer rotating or steady burn type warning lights.

For estimating the relative speed of the snowplow for following vehicles, operators prefer flashing lights with alternating (i.e. "wig-wag") (55.3%) pattern and random sequences (31.7%) for warning light patterns. Very few respondents prefer flashing all at same time (such as hazard flashers) and steady burning warning light patterns to estimate the relative speed of the snow plow for following vehicles.

For the increased brightness of warning lights especially for other plow truck drivers following behind during snow removal operations, higher percentages of responding operators (76%) believe warning lights are never too bright, while a lower percentage (24%) of operators believe that warning lights can be too bright for those following behind a plow truck or other vehicles. In particular, operators who consider warning lights to be too bright suggest having lower intensity settings especially at night. Another option operators suggest is to keep a reasonable distance away from the plow truck. In general, operators who think warning lights are not too bright consider that brighter lights are better to warn drivers approaching from the rear. Nearly 80% of the respondents do not have a day versus night settings in their vehicles to accommodate the increased brightness caused by warning lights. About 15% of respondents do have day versus night settings in their vehicles, which are usually manually operated except for a few operators who have automatic settings in their vehicle to change between day and night settings.

Devices or mechanisms used to keep lights clear of the snow are not common, with respondents (98.5%) not having any mechanism. One operator mentioned having a wind deflector on the vehicle and another operator manually cleans the lights.

Work Lights

Work lights are floodlights or spotlights mounted at various places on the truck exterior for illumination of specific locations such as a wing-plow, under-body plow, top of a truck bed, spreader-spinner, cab-steps, etc. Work lights enhance safety and convenience for the truck operator. Work lights are most commonly located on the side and rear of the vehicles. Very few respondents have work lights located on the front of the vehicle. In addition, flood lights are commonly used as work lights, rather than spot lights. In addition, some respondents also mentioned using work lights on spreaders and wing plows.

Halogen bulbs (55.6%) are the most commonly used light bulb for work lights, followed by LEDs (37.9%). Very few responding agencies use incandescent and HID bulbs for work lights. Most operators use white color (95.1%) for their work lights. A few operators indicated using amber, blue, and amber-white color for their vehicle work lights. Respondents indicated they prefer additional work lights on tow plows, wing plows, top of the cab, under body lights, top of sanders (to keep track of materials), and some additional flood lights on the rear.

Retro-reflective markings

Retro-reflective markings are typically added on the rear of the vehicle and side of trucks. Retro-reflective markings increase visibility of the vehicle at night and during low-light conditions. Survey responses indicate that approximately 80% of the respondents have some sort of the retro-reflective materials on their snowplows. Only, 20% of the respondents did not use retro-reflective materials. The most commonly used patterns for reflective markings are body outline (rectangle) and horizontal stripes (27%). A few respondents indicated they have chevrons and/or vertical stripes patterns for reflective markings on their vehicles. The most commonly used color combinations are red and white. Some of the other combinations reported by respondents include orange and white, red-white-yellow, black and yellow, and red-white-blue. In addition, retro-reflective markings are commonly used on the rear of the vehicle, and less commonly on the side of the vehicle. Very few respondents have retro-reflective markings on the plow (back or edges).

In general, most operators (51.7%) believe that retro-reflective materials are very effective when kept clean. Additionally, operators believe that retro-reflective materials increase visibility of the plow to other drivers and vehicles on the road (33.6%). A few operators (5.6%) indicated that they felt that retro-reflective materials do not have any impact in warning approaching drivers.

Furthermore, 61% of operators prefer having additional retro-reflective markings on snow trucks and 39% of operators do not prefer having additional retro-reflective markings on snow trucks. In particular, one operator preferred having more retro-reflective markings but thinks that keeping them 100% clean becomes difficult resulting in reduced effectiveness.

Some of the locations operators prefer having retro-reflective materials include the edges of the plow, side and rear of the wing plow, the side and rear of the truck, at the rear on sander chute, and the back of "V" beds. Interestingly, one operator cautioned too much retro-reflective markings can take away the effectiveness of warning lights.

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research for winter highway maintenance

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