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Naturalistic Experiment for Surface Transportation: A Study of Snowplow Lighting under Winter Conditions

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Abstract: Inclement winter weather poses a safety risk to all road users, primarily due to roads covered with snow or ice and substantially reduced visibility. The winter road maintenance vehicles used are often larger and slower moving than the surrounding traffic and often become a hazard themselves. To enhance visibility and safety, agencies equip their fleets with lighting to make them more visible to the surrounding motorists. In Alberta, Canada, the use of amber-only lights is currently permitted for maintenance vehicles. To evaluate whether the addition of light colors could measurably improve road safety for snowplow trucks and motorists, we conducted a human reaction field study (n=384 trials) and a general public survey (n=454 participants), testing several combinations of light colors. The field experiment revealed that amber-only lights resulted in slower reaction times, whereas amber-blue and amber-white performed better. Survey results demonstrated a preference for amber-white lighting, which was deemed the most effective setup. The survey also indicated that lighting perception varies across age, gender, and specific types of driver's license among demographics. While this research identifies optimal lighting configurations and underscores targeted policy-making and operational strategies, its direct impact on road safety remains to be determined. It is possible that shorter perception/reaction times given the lighting changes could reduce the number of collisions. Incorporating these results into existing practices could potentially enhance road safety standards, making winter roads safer across jurisdictions in North America.

Keywords: winter road maintenance vehicles; reaction times; public survey questionnaire; experiment; snowplow; lighting; winter conditions

1. Introduction

Active winter weather conditions pose a significant hazard to motorists, often leading to slippery road surface conditions (RSC), reduced visibility, and physical obstructions due to snow. Deteriorating RSC conditions put motorists at an increased risk of fatal or injurious collisions in addition to reduced mobility of goods and services. For example, in December 2017, Canada saw nearly 14,000 injury collisions (Royal Canadian Mounted Police 2019). Although it is the responsibility of drivers to adapt to conditions, local road authorities also must ensure that their roads are in the best condition possible. Therefore, agencies worldwide work to ensure that their road networks are maintained via their winter maintenance programs to keep their people safe and moving. Highway maintenance contractors (HMCs) often use trucks and service vehicles outfitted for winter road maintenance (WRM) that are often larger and travel slower than the surrounding traffic (for example, snowplow trucks and graders), thereby becoming a road hazard, especially in low visibility conditions. One major issue is the motorists' inability to visually assess the snowplow's location and movement under these adverse conditions, creating unpredictable and unsafe driving situations. The combination of snowfall and the formation of trailing snow plumes from snowplowing reduces a snowplow's visual presence significantly, leading to increased risks of collisions. Past studies have indicated that nearly 70% of collisions involving snowplows are rear-end collisions (Bullough, et al. 2001), and the Iowa Department of Transportation (DOT) found that most collisions resulted from reduced visibility (Kamyab and McDonald 2003).

To mitigate these hazards, warning light fixtures and highly reflective surfaces are installed on snowplows to provide additional visual cues to approaching motorists. In several regions, regulations permit the use of amber lights only on snowplow trucks. However, collisions continue to occur even with these lights. Alberta Traffic Collision Statistics report that in 2021, there were 2 such collisions, 9 in 2020, 2 in 2019, 5 in 2018, and 2 in 2017 related to motorized snow vehicles (Government of Alberta n.d.). Suggestions have been made for using additional colors to help increase their visibility on the roads, with blue lights being the most requested color. Despite the number of studies on using additional or alternate maintenance vehicle lighting colors, few have been done under operational field conditions for definitive, conclusive results.

Addressing this critical gap, an extensive and holistic study was designed to examine alternative WRM vehicle lighting schemes under varying winter operating conditions. The objective was to garner empirical and quantitative evidence that could substantiate whether these proposed changes could yield tangible safety improvements. Central to this research initiative was a controlled field experiment that measured participants' reaction times under different lighting color setups. These setups differed exclusively in their active lighting configuration, while passive reflectors remained the same. Dashcam recordings from a chase vehicle were integral to this study, serving not only to validate the accuracy of the field experiment but also to establish a basis for the subsequent in-depth analysis of public perception.

Building on this empirical foundation, the study extended to engage a broader segment of the public through a uniquely designed survey. This questionnaire was widely distributed online, targeting the diverse population of Alberta to further aid in color detection, recognition, and perception. Survey participants viewed video recordings and still images of the various lighting schemes taken from the field experiment and then provided feedback on each setup via a series of questions. The collected survey data was subsequently analyzed to determine how the general public interprets each color scheme, which scheme was subjectively more perceptible, and if there were any trends in the general public's responses. This element of the research is particularly notable for its thorough three-way comparison of amber-only, amber/blue, and amber/white lighting schemes, an approach that has not been explored previously.

The insights gained from these two complementary approaches hold the potential to significantly enrich our comprehension of how the broader public perceives lighting configurations. This enhanced comprehension, when applied, can serve as a valuable resource in shaping policy decisions, enhancing safety protocols, and refining operational strategies concerning the visibility of WRM vehicles and overall road safety. Such insights can contribute meaningfully to advancing policies and practices aimed at safeguarding the well-being of both motorists and maintenance vehicle operators during adverse weather conditions. However, it is important to acknowledge certain limitations that may impact the interpretation of our findings. Firstly, the experiment was exclusively conducted during daytime hours, which may limit the generalizability of our results to nighttime driving conditions. Secondly, this study focused solely on the addition of blue and white lights to the existing amber setup, omitting consideration of other colors. While this approach enabled a focused investigation into the effects of specific lighting combinations, it also restricts the breadth of our analysis. We recognize the importance of exploring a wider range of lighting options in future research to comprehensively assess their impact on driving behavior and safety.

2. Literature Review

2.1. Passive Visibility Equipment

Visibility obstruction, a significant factor contributing to the risk of collisions between snowplows and motorists, underscores the importance of passive visibility equipment. Passive visibility equipment enhances a vehicle's detectability through their reflective properties. These elements passively reflect incident light back to its source, effectively mitigating risks associated with poor visibility conditions. To understand the conditions that drivers face during inclement weather, Kang et al. (2008) studied the effects of fog on drivers' performance (Kang, Ni and Andersen 2008) by putting subjects under different weather and visibility conditions using a driving simulator. Their behavior was closely observed by recording their headway distances with leading vehicles and their adopted speeds under each driving condition. They found that subjects tended to decrease their headway distance in lower visibility conditions to likely better see and follow the leading vehicle. On the other hand, drivers could not estimate relative speeds accurately in these conditions.

One common factor affecting vehicles of all types in the winter, including snowplows, is the build-up of snow on the back, especially those with vertical rear ends. One way to reduce the snow accumulation on the back of snowplows is to use a rear deflector. Stutze et al. (1995) showed that installing the deflector eliminates snow build-up, facilitating greater visibility of the snowplows' taillights to motorists (Stutze, et al. 1995).

Despite deflectors initially showing signs of safety benefits, Kamyab et al. (2002) found them ineffective in enhancing safety during operational activities (Kamyab, McDonald and Storm 2002). Instead, they discovered that retro-reflective markings were more effective in improving the visibility of snowplows, especially in low-light conditions. They noted that several jurisdictions in the U.S. utilized retro-reflective tape to enhance their snowplows' visibility effectively. Additionally, Lan et al. (2019) found that the perception-reaction times of motorists were significantly longer when following maintenance vehicles with no retro-reflective markings and were a significant contributing factor in rear-end collisions (Lan, et al. 2019). However, there was no accounting for snow accumulation on the reflectors during operations.

2.2. Active Visibility Equipment

Active visibility equipment refers to devices that actively emit light or signals to enhance the visibility of a vehicle. Examples include headlights, strobe lights, and LED warning lights. Unlike passive visibility equipment, which relies on reflecting external light sources, active visibility equipment generates its own illumination, making vehicles more noticeable in low-light and adverse weather conditions.

Improving the visibility of WRM vehicles is essential to solving the safety issue at hand (Verma, et al. 2019). These vehicles play a vital role in improving roadway conditions and ensuring transportation service performance, particularly in challenging weather conditions (Kamjoo, et al. 2023). It is also important to assess how drivers perceive these improvements in their ability to evaluate the snowplows' relative distance, speed, and direction of movement. Visibility can deteriorate rapidly during inclement weather, and these parameters should be incorporates into experiments (Bullough, et al. 2001).

In an early lighting study, Hanscom et al. (1990) conducted experiments to test the effectiveness of rotating, strobing, and flashing lights to provide enough warning to motorists of potential dangers on the roads (Hanscom and Pain 1990). By comparing drivers’ response times to each lighting type, they found that rotating and strobe lights were superior in drawing their attention to hazards on the road. However, when either of these two was used alone, drivers could not accurately estimate the speed at which they approached the potential hazard. Alternatively, flashing lights were better for determining the speed and course of movement, but their capability to draw drivers’ attention was not as effective. As a result, the authors recommended combining the strobing or rotating lights with the flashing lights to maximize visibility and minimize the drivers’ response times.

Bullough et al. (2001) found that the effectiveness of different lighting fixtures depended on factors such as the type, the color or combination of colors, their mounting locations, the luminous intensity, and the weather conditions (Bullough, et al. 2001). They stated that rear lighting configurations on snowplows serve two distinct purposes:

1. To alert other drivers to their presence; and

2. To provide cues to drivers about relative distance, operation speed, and direction of travel.

In their study, Bullough et al. (2001) conducted two experiments to compare different rear light configurations of WRM trucks, including snowplows. In their first experiment, they surveyed county snowplow operators' volunteer subjects to rate the visibility of various light configurations during different weather conditions based on their current driving experience. Subjects rated the steady-burning LED light bars as the highest amongst the alternatives, including the conventional flashing amber and alternating flashing amber and red lights. This finding was similar to the study conducted by Indiana State DOT, whereby LEDs were perceived as the brightest form of illumination regardless of shape or mounting system (McCullouch and Stevens 2008). Furthermore, they compared two lighting color schemes and found that their participants perceived amber as the brightest setup, followed by bright blue.

In their second experiment, Bullough et al. (2001) compared the closure detection times of the steady-burning warning light to the flashing light configuration in a field test. Two vertical LED light bars were mounted on the left and right back edges to provide motorists following behind a sense of the snowplow’s width. This setup was compared to a typical flashing amber configuration. In their test, the driver followed the snowplow at a constant speed of 48.3 kph (30 mph) and a fixed distance of 100m. The snowplow would slowly decelerate by taking the pressure off the accelerator. The driver would then indicate once they observed that the truck was decelerating or that the relative distance was closing. The time from when the snowplow began to decelerate to when the driver observed that deceleration was recorded as their reaction time. Each lighting configuration had 24 trials for a total of 48. Their results showed that the average perception time was 9.8 seconds for the vertical lighting and 12.4 seconds for the flashing amber lights. The improvement of 2.6 seconds at 48.3 kph (30 mph) corresponded to a driving distance of 35 meters. The authors stated that the shortened response times gave the driver more space to stop or go around the snowplows. The results of their work were in line with previous studies, concluding that strobing and flashing lights were better for visibility. In contrast, steady-burning lights were better for estimating location and speed (Bullough, et al. 2001).

Two similar U.S.-wide surveys, conducted by Kamyab et al. (2003) and Howell et al. (2015), respectively, explored the policies adopted by the Departments of Transportation (DOTs) and highway agencies on their usage of warning lights (Kamyab and McDonald 2003, Howell, Pigman and Agent 2015). Over 34 State DOTs and individual counties responded to the two surveys. Both studies found a wide variety in each state's use of types and colors of warning lights, as each state DOT experimented with different lighting settings to improve the visibility of their highway maintenance vehicles. However, it was common among most departments to use amber-colored warning lights, sometimes supplemented by red, white, or blue. Additional warning lights were often used on snowplows due to the poor weather conditions in which they are typically deployed. Based on the responses to the surveys and the work done by Gibbons et al. (2008), the Kentucky Transportation Centre issued several recommendations, including employing amber and white colors as warning lights for all roadside assistance vehicles, using slow frequency asynchronous flashing patterns, placing warning lights at the highest elevation possible and against dark backgrounds to improve contrast, and using LED lights of at least 4,000 lumens for daytime operations and 1,650 lumens at night (Gibbons 2008).

Muthumani et al. (2015) tailored their study specifically around warning lights used during snowplow operations (Muthumani, Fay and Bergner 2015). While most agencies were still testing other colors like blue, white, and green, amber was still the predominant color used for warning lights. Operators also reported favoring white when used with amber since this combination becomes more visible during storm conditions. Furthermore, the researchers confirmed the need for strobing lights in conjunction with steady-burning lights to detect the snowplows and accurately determine their relative speed and movement. It was also noted that retro-reflective tape markings were a practical and effective form of passive visual warning to approaching vehicles as long as they were kept clean and unobstructed.

Ullman (2000) studied the effects of different warning light colors and combinations of colors on drivers' behavior utilizing a survey and a field experiment (Ullman 2000). First, drivers from three Texan cities were surveyed on their interpretation of the different light colors and combinations. Then, under non-winter daytime and night-time conditions, field tests were conducted where the average speeds and usage of brakes of motorists allowed researchers to observe and record their reactions when exposed to different light color combinations. The survey results showed a marginally higher degree of danger was perceived with amber/blue than with amber lighting alone. However, drivers perceived the amber/red combination as the most dangerous. The average speeds were significantly lower in the field tests when amber/blue was used instead of amber-only lights. Furthermore, the combination of red/blue/amber lights resulted in the highest usage of brakes, while the amber/blue combination was the second highest. Both were higher than amber only. Even though the study results were inconclusive, the author recommended using the amber/blue combination rather than amber-only lights in hazardous situations or when speed reduction is required.

Another light color study was conducted by Missouri's DOT with consideration to green lights (Brown, et al. 2018). Their study compared four lighting combinations: amber/white, green only, green/white, and green/amber lighting setups, using participants and a simulator in a field setting. They monitored the driver's speed, first blinker distance, merge distance, and combinations thereof. The simulator experiment found that amber/white had the highest visibility day or night, but many regarded it uncomfortably bright with some distracting glare. Green lights on their own were the most effective at slowing down vehicles and were regarded as the most comfortable on the eyes at night. Green lights combined with other colors result in slower vehicle passage compared to situations without adding green lights. This study was the first of its kind regarding green lights and brought attention to their use.

A different research study examines how different warning light setups affect the visibility of snowplows, specifically emphasizing the role of green lights (Fakhrmoosavi, et al. 2021). Another green light study was conducted by Michigan State University and the Michigan DOT in 2020. To improve the visibility of their WRM vehicles, they have included green lights in their lighting setups since 2016 (Zockaie, et al. 2020). In this follow-up investigation, they wanted to determine how the vehicles' visibility improved. The observers' primary concerns were the light's perceptiveness during the day and the amount of glare during the night. Overall, they found that a green/amber combination with a single strobing pattern best balanced both day and night concerns while also improving conspicuity.

In Canada, the Ontario Ministry of Transportation conducted a study on the most effective way to improve the visibility and recognition of snow removal equipment. They examined nine different light color and sheeting combinations in winter conditions during day and night, though the exact details of their experiment were not provided. Their tests found that a fluorescent yellow-green and black checkerboard pattern provided the best unlit or passive visibility. The study also demonstrated that the blue-colored lights were the most visible during both day and night at lower intensities in single-color setups, significantly reducing motorists' glare. However, they also indicated that multi-colored lighting schemes were more effective than single-colored (Ontario Ministry of Transportation 2015). The details of their overall experiment in their presentation were minimal and generalized, with no amount of data presented, analysis methods explained, or discussion of results made.

The government of Saskatchewan was the first jurisdiction in Canada to use the amber/blue combination for roadside assistance vehicles (THE CANADIAN PRESS 2017, Canadian Underwriter 2017). Officials claimed that the new warning light configuration would be easier to see from long distances, giving drivers more time to react to a hazardous situation. However, the government did not present studies or analyses of the policy change results.

While prior studies have mentioned the potential advantages of various lighting setups, a gap exists in comprehensive research that quantitatively evaluates their impact on safety, visibility, and public perception, particularly under diverse winter conditions.

This study addresses this gap by conducting a controlled field experiment to measure participants' reaction times under different lighting color setups for snowplows. Additionally, this study included a general public survey to assess aspects such as color detection, recognition, and perception. Notably, this research undertakes a unique three-way comparison involving amber-only, amber/blue, and amber/white lighting schemes, which has not been previously investigated.

3. Project Methodology

3.1. Naturalistic Field Experiment

A human reaction (i.e., naturalistic) experiment was proposed for this study to determine the most visually noticeable lighting setup, comparing the current amber-only standard to an amber-blue or amber-white setup. We chose a real-world field condition experiment as it has been shown to provide evidence of the lights' effect on human response times. This method takes the concept initially done by other active visibility studies by Hanscom et al. (1998), Ullman (2000), Gibbons et al. (2008), Muthumani et al. (2015), and the Ontario Ministry of Transportation (2015). However, these studies were limited to stationary settings and controlled spaces such as a yard or fixed road section. To fully understand the lighting factors, we conducted our naturalistic field experiment during the operational road servicing carried out by partnered contractors and volunteer participants. We then recorded their reaction times under live field conditions. This section outlines the study's experimental design and setup and the equipment, vehicles, and locations used.

3.1.1. Experiment Design

The design of the experiment was set up as lead-and-follow. A snowplow truck, equipped with one of three different lighting schemes, would carry out its operational task of plowing the road. Behind them, the subject would drive a chase vehicle and whose reaction times would be recorded. The recorded reaction time would be when the subject noticed the snowplow slowing down and their separation distance closing. As per previous studies, the quicker the reaction time, the more effective the lighting scheme will be in providing visual cues to its relative speed, distance, and location. Based on these criteria, the most effective lighting scheme could be categorized as the safest snowplowing scenario since it could be considered more visible, allowing passing motorists to adapt more effectively.

In this study, the three lighting setups tested were amber-only (the current standard in Alberta), amber-blue, and amber-white. The goal was to have each volunteer subject complete several trials for each lighting setup, all on the same day during the same storm event. To properly conduct this experiment in the field, a minimum number of participants was required, each with a specific role. **Figure 1** shows who the volunteers are and how their roles were allocated. These roles and their tasks are outlined in **Table 1**.

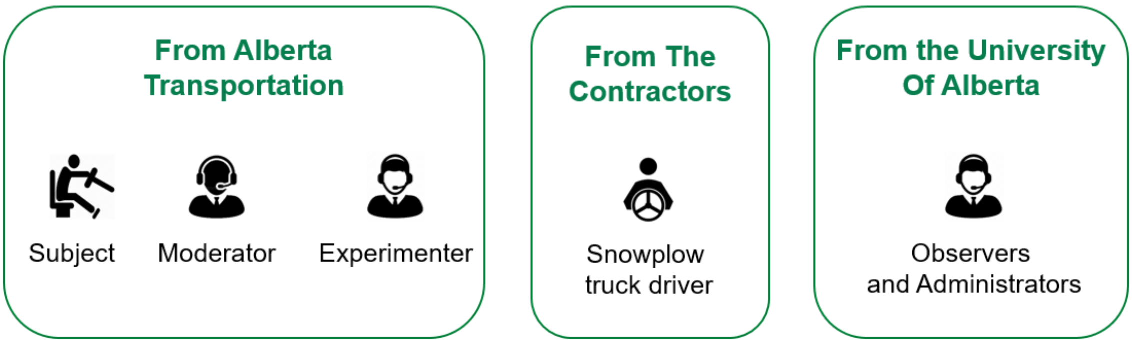

Figure 1. Project participants and their allocated roles.

Table 1. Roles and their tasks within the field experiment.

Role Title	Main Tasks
Snowplow Truck Driver	1. Field experiment lead/supervisor while deployed 2. Takes decelerating instructions from the Experimenter 3. Takes care of the snowplowing activity 4. Maintains a 50 to 60 km/hr speed when not decelerating
Experimenter	1. Field experiment main-hand while deployed 2. Situated in the plow truck 3. Coordinates with the Moderator in the chase vehicle 4. Instructs the driver to decelerate 5. Starts/stops trials 6. Records the reaction times and the start and end distances
Moderator	1. Situated in the chase vehicle 2. Monitors the separation distance for each trial 3. Will be the primary source of contact and coordination for the Experimenter 4. Ensures video recording of the entire experiment
Subject	1. Follows the snowplow truck at the desired distance and speed 2. Identifies when they perceive the snowplow truck is decelerating and/or the separation distance is closing

Alberta Transportation (AT) volunteers were divided into two groups from two separate regions, the southern region and the central region. Each office had a primary point of contact responsible for mobilizing the volunteers for deployment. The main point of contact was also responsible for contacting the contractor's foreman to coordinate vehicle deployments from the contractor's workshop.

To ensure the lighting schemes were correctly tested, the snowplow would slow down without brakes by the driver releasing the accelerator and allowing the truck to slow on its own. Additional instructions were given to the field participants to ensure that conducting a trial on vertical grades was avoided and to minimize horizontal curves, if possible. The subject in the chase vehicle would have their reaction time recorded from the moment the plow started to slow to when the subject articulated their perception of the change in speed or separation distance. **Figure 2** shows the vehicle arrangement and the location of each role.

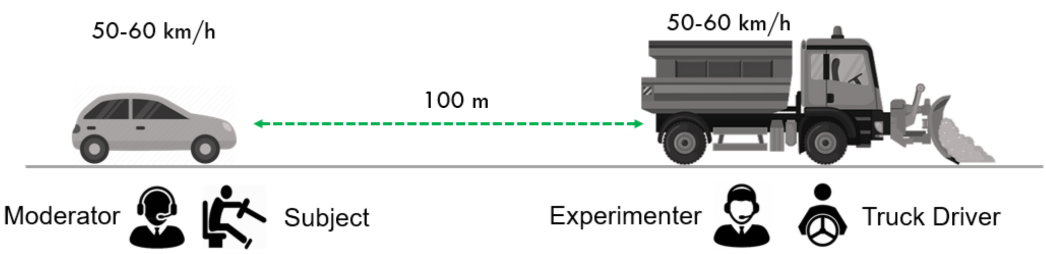

Figure 2. Experimental setup, including the snowplow and chase vehicle.

Because the field experiment was conducted on public roads with live traffic and under natural environmental conditions, proper communication and step-by-step procedures were required to maintain the safety of everyone involved. A detailed, step-by-step process and prewritten communication script were created to inform and train participants on their tasks and help inform their expectations. By following the process, the volunteers could execute the experiment on their own safely and record a set of reaction times.

Every reaction recorded by a subject was considered an individual trial for the particular light they were following at that time. At a minimum, 12 trials were done for each of the three lighting setups for each deployment subject. No maximum number of trials was set for each subject per setup, and they were free to conduct more trials if time permitted. If they were successful in completing the tasks, the deployment was considered complete. If the volunteers could not experience all three lighting setups on the same day or during the same storm event, that deployment was considered partial or incomplete. This classification helped reduce the effects of day-to-day variability in daylight intensity, cloud cover, or volunteers' health and mental states. Setting a minimum number of trials also prevented the data set size from being too small for sufficient statistical analysis and rigor.

3.1.2. Vehicles

Two contractors volunteered to participate in this study and supplied the snowplow trucks from their operating fleet. The same make, model, and setup were used for all the selected trucks to reduce variability. Both contractors used their 2019/2020 Western Star tandem axle truck chassis with their snowplow configuration and an additional extension wing for plowing the shoulders of the roads. The checkerboard pattern on the rear of the trucks is the current standard required in Alberta. **Figure 3a** and **Figure 3b** show examples of the lighting setups from Volker-Stevin and Mainroad, respectively. Both contactors' vehicles had all three lighting setups at various experiment stages. **Figure 3c** is taken directly from the dashcam footage of one of the deployments, and this source video was also used in the survey.

(a) (b) (c)

Figure 3. Plow truck lighting setups: **(a)** Volker-Stevin – example of Amber-Blue; **(b)** Mainroad – example of Amber-White; **(c)** Dashcam footage used in survey.

The chase vehicles used were intermediate-sized SUVs and half-ton pickup trucks from Alberta Transportation's vehicle fleet, specifically the Chevrolet Equinox and Silverado. These vehicles were chosen to best reflect the most common size class of vehicles on Alberta roads. Because the chase vehicle would follow the plow trucks during actual operations, it was vital that they were also visible to other motorists and were equipped with flashing amber lights for safety. The chase vehicles were otherwise unmodified.

3.1.3. Study Areas

The study area for the field experiment was divided into two regions, South and Central. Volker-Stevin worked in the South region around the Elbow River area west of Calgary, deployed on Highway 66, with their volunteer base from the Calgary offices. Mainroad worked in the Central region around the counties of Ponoka and Lacombe and deployed mainly on Highways 2A, 604, 611, 822, and 827, with volunteers coming from the Red Deer offices.

3.1.4. Procedures & Communication

The initial intent was to conduct the field experiment during a winter storm to facilitate the inclusion of blowing snow as a factor in reduced visibility in determining the lights' effectiveness. Therefore, the contractors monitored weather through meteorologists for their designated region and the University of Alberta (UAlberta) Group via Environment Canada's website. When a storm was forecasted within 48 hours for a region, the contractor in that region would contact the UAlberta Group's project manager to jointly decide if the conditions would be viable. Viable conditions meant the forecast had a minimum 60% chance of snowfall for at least 4 hours and no freezing rain. If jointly deemed feasible, the project manager would contact the region's AT volunteer point of contact and inform them that deployment would go ahead. The AT point of contact then confirmed the availability of the volunteers and coordinated deployment with the contractor's foreman for the area.

Executing the experiment safely and efficiently required a high level of coordination and communication between the snowplow and the chase vehicle. During a deployment, all volunteers involved were asked to use the radios provided to help them with inter-vehicle communications along with the step-by-step guide and script developed as further assistance to keep them organized and on task. Throughout the experiment, the volunteers were free to modify or create their script and use alternative methods of communication between vehicles afterward to best suit their needs and levels of comfort.

The safety of everyone involved in the field was a significant concern throughout the project, as it was done on active roads. The contractors and the UAlberta Group continuously monitored weather forecasts and road conditions to mitigate the risks. If any incident occurred, the safety procedures would default to the contractors as they have the greatest understanding of the processes for their regions. It would be supplemented by AT's safety processes and the University would provide additional record-keeping and documentation.

3.1.5. Equipment and Forms

The data was recorded by the volunteers in the field using the provided data collection sheet. The equipment provided to conduct the experiment included radios for inter-vehicle communications, a stopwatch for reaction times, a rangefinder to measure the distance between the chase vehicle and the snowplow, and a dash camera to mount on the chase vehicle to record the experiment along with additional flash memory cards for the cameras. The video recordings were used to review each deployment and potential abnormalities in the data and shorter clips were used in the general public survey.

3.1.6. Data Filtering

The collected data was scanned and emailed to the research group, allowing immediate cleaning and analysis. Hard copies of the data forms and the video cards from each deployment were collected in person or sent via certified mail to the research group.

Not all deployments were completed since the weather was not always consistent, nor were the volunteers always available for the full deployment duration during the deployment period. Partial deployments were omitted from the final analysis since they would introduce day-to-day variability when not experiencing the light combinations on the same day. Partial deployments would also create an uneven number of trials for each lighting setup. Two days of deployments were omitted because the volunteers only completed trials for one lighting scheme or missed one for the day. The final tally of complete deployments was six, three in each region. The minimum of 12 trials per subject per lighting scheme was also met for these six deployments, with one deployment having up to 16 trials per lighting setup. In several cases, trials ranged from 12 to 14 per deployment, leading to differences in trial numbers for each lighting scheme. Due to the data set size, data for all six runs were analyzed together rather than divided into their respective regions. A total of 384 trial runs were conducted across the three lighting setups.

3.2. General Public Survey Questionnaire

To expand the reach of the experiment to more participants outside of the prohibitively time-consuming field experiment process, the research group developed a widely distributed general public survey. The purpose of the survey was to gather the public's feedback on the lighting colors and how they perceive them. The survey was also devised to provide insights into response trends and patterns based on various demographic variables not captured in the field experiment.

3.2.1. Survey Design

Surveys require sufficient time for participants to respond, and the team chose a length of at least one month. Therefore, the survey was conducted from April 25, 2022, to May 31, 2022, and distributed via community posts, web pages, and social media in the various towns, cities, and communities around Alberta. It was designed as an online questionnaire with images and videos for the participants to view and answer questions. The survey had 35 questions with 15 demographic and descriptive questions, six open-ended opinion questions, 12 lighting questions, and two post-survey follow-up questions for filtering. The survey was designed to be distributed virtually, allowing for the use of images and videos with sliders and multi-choice check boxes.

The video clips chosen for the survey were from the field experiment from one of the many deployments. All the videos were taken from the same deployment to avoid day-to-day variability. From the original dashcam videos, 20-second-long clips were cut that met the following criteria:

1. No vertical curves;
2. Minimal horizontal curve;
3. Some snow plume interaction;
4. Similar distances between the camera and truck;
5. Same speeds of travel; and
6. Clearly visible lights for at least 80% of the video clip.

3.2.2. Distribution & Data collection

Link distribution was primarily achieved through public engagement via municipal websites and social media accounts. Contacts for these municipalities came from a database of city managers and officials that Alberta Municipal Affairs maintains. Participants were also encouraged to share the link with friends, family, and peers.

Distributing the survey this way reduced selection and participation bias and reached the broadest population possible, generating a sample that mostly reflected the general population of Alberta. The survey was also distributed using community, city, village, county, and town websites and social media for the greatest exposure to the greatest variety of people possible.

3.2.3. Survey Data Filtering and Screening

Through our distribution, a total of 1,158 surveys were started. Since the survey was open to the general public in a widely distributed format, there was a wide range of completeness and quality of the responses. As part of the ethics condition, participants were given several ways to opt out or request not to be included in the collective data set. Therefore, the data needed to be screened and filtered for non-applicable responses and only include those that met the completion and participation guidelines. **Table 2** outlines the filtering process, how many responses were removed at each step, and the final count of acceptable responses according to the conditions set forth by the ethics protocol. We used 454 responses for analysis.

Table 2. Survey data filtering process.

Action	Filtering Question No.	Number of Responses Removed	Remaining Responses
Starting count of total responses		1158	
Remove all surveys with a response of "No" to "For confirmation, do you wish to have your responses be a part of the study?"	36	27	1131
Remove all surveys with unreliable responses	2, 4, 5, 8	7	1124
Remove if the survey was incomplete (as outlined by the ethics process)	19 to 30	670	454
Final count of complete surveys for analysis		454	

4. Analysis and Discussion

4.1. Field Experiment

4.1.1. Preliminary Data Analysis

Table 3 provides a preliminary overview of the data collected and used in the reaction time analysis.

From this preliminary analysis, the mean reaction time for amber-only was approximately 1.3 to 1.4 seconds longer than amber-blue or amber-white, respectively. The variance in the reaction times was also larger with amber-only than in the other two setups. Reaction times to amber-blue and amber-white were similar. To visually explore the data, the boxplot of the data set shown in **Figure 4** illustrates the data spread, its statistical minimums and maximums, its median, its 25th, 50th, and 75th percentiles, and any outliers.

Figure 4 shows that the minimums, maximums, median, and percentiles for amber-blue and amber-white were lower than for amber-only. These values are summarized below in

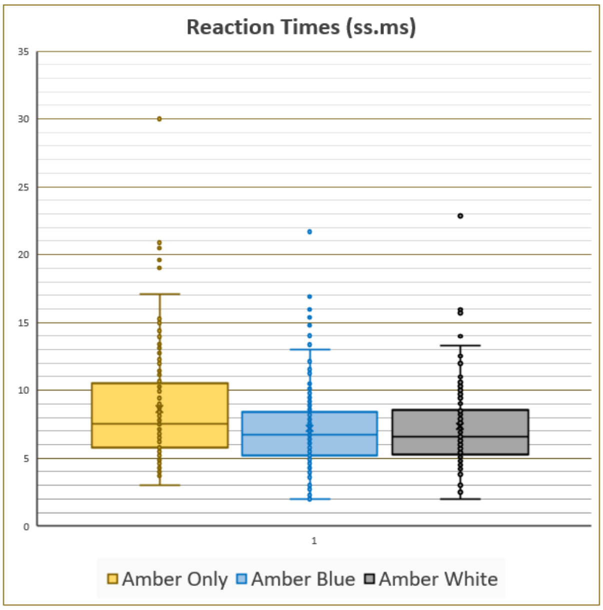

Figure 4. Boxplot of the reaction times dataset.

Table 4.

Table 3. Reaction Time descriptive statistics.

Statistic	Amber Only	Amber-Blue	Amber-White
No. of Trials	130	133	121
Min Reaction Time	3.00	2.00	2.00
Max Reaction Time	30.00	21.67	22.84
Mean Reaction Time	8.63	7.24	7.33
Var. of Reaction Time	17.26	10.56	9.13

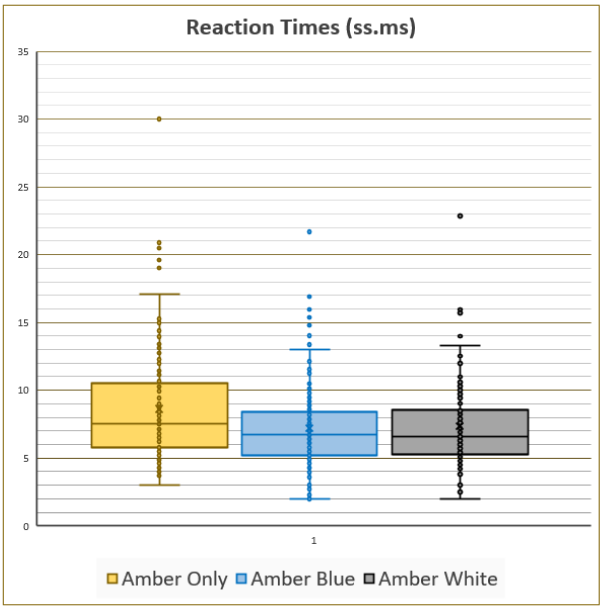

Figure 4. Boxplot of the reaction times dataset.

Table 4. Reaction times statistics from the boxplot.

Statistic (seconds)	Amber Only	Amber-Blue	Amber-White
Minimum	3.00	2.00	2.00
25th percentile	5.81	5.20	5.30
Median	7.54	6.70	6.60
75th percentile	10.54	8.40	8.55
Maximum	17.06	13.03	13.31
Extreme outlier	30.0	21.72	22.80

Using the descriptive statistics and boxplot, it is clear that the amber-only light setup has longer reaction time statistics with increased variability and spread in those reaction times. The boxplot also highlights three potential extreme outlier values for each color scheme. After revisiting the dash camera videos to review each instance, there appeared to be no problematic cause for these values and, thus, no valid reason to remove any of them. Therefore, these extreme values have been maintained throughout the rest of the analysis.

4.1.2. Pairwise T-Test Comparison

After preliminary data analysis, we determined whether the reaction time difference was statistically significant. A series of pairwise comparisons of the three lighting setups were conducted. The statistics compared were the means and variances of the reaction times for each lighting setup, represented by the following hypothesis:

$H_0 = x_1 - x_2 = 0$ The statistics in question are statistically equal

$H_1 = x_1 - x_2 \neq 0$ The statistics in question are not statistically equal

The metric used to gauge this was the p-value, $\alpha = 0.05$. If the p-value was 0.05 or greater, we failed to reject the null hypothesis and state that the means/variances were statistically equal. If the p-value was less than 0.05, we could reject the null hypothesis and consider the alternative hypothesis as the means/variances were statistically different.

The first comparative test was the *t*-test between each pairing to determine if the difference in their means was statistically different. **Table 5** summarizes the various *t*-tests conducted.

Table 5. Pairwise T-tests on mean reaction times.

Factors	Amber-Only vs Amber-Blue	Amber-Only vs Amber-White	Amber-Blue vs Amber-White
t-value	3.00	2.80	-0.20
Degrees of Freedom	244	236	252
p-value	0.00	0.01	0.83
95% CI lower bound	0.47	0.40	-0.86
95% CI upper bound	2.30	2.20	0.69

The *t*-test pairing results show that the mean reaction times for amber-only were statistically different from amber-blue and amber-white. It also demonstrates that the mean values between amber-blue and amber-white were not statistically different. Recalling that the mean reaction time from amber-only was higher than amber-blue or amber-white, it suggested that the inclusion of blue or white light resulted in a faster reaction time from the subjects.

4.1.3. Pairwise ANOVA and Variance homogeneity tests

As noted in the preliminary analysis, the variance of the reaction times was higher with amber-only. To determine if this difference was statistically significant, we conducted an Analysis of Variance (ANOVA) to explore if the variances within the reaction times were the reason for the results. When conducting an ANOVA analysis, it was crucial to run it based on proper variance homogeneity assumptions. Therefore, we undertook the Bartlett Test of Variance against $\alpha = 0.05$ to test whether the pairing variances were equal before conducting the ANOVA. The results from each pairing analysis are displayed in **Table 6**.

Table 6. Bartlett variance test and ANOVA analysis.

Statistics	Amber-Only vs Amber-Blue	Amber-Only vs Amber-White	Amber-Blue vs Amber-White
		Bartlett Test	
p-value	0.005	0.001	0.422
Variances are:	Unequal	Unequal	Equal
		ANOVA Analysis	
F-value	8.98	8.06	0.05
p-value	0.00	0.01	0.83

The Bartlett test showed that the variances in the reaction times of amber-only were statistically different from those of amber-blue and amber-white. Likewise, the test revealed that the variances between amber-blue and amber-white were not statistically different, suggesting they were equal. With the variance homogeneity determined, the ANOVA analysis was then done with the variance equivalencies taken into account. Altogether, it became clear that the variance of the reaction times associated with amber-only lights was statistically longer and greater, respectively, than with amber-blue or amber-white. In turn, the ANOVA analysis revealed that the differences from the amber-only mean values were not a result of the differing variances, even though they were statistically unequal.

Interestingly, there was no statistical difference in reaction time performance between the amber-blue and amber-white setups. This result was unexpected as the Ontario study found a preference for blue lights. However, the results did coincide with Ullman (2000), where adding any second color (e.g., blue or red) resulted in an improvement over having a single color (Ullman 2000).

4.2. General Public Survey Analysis

4.2.1. Participant’s Description

From the survey, five demographic categories are of particular interest for study: 1) general responses, 2) age-based, 3) gender-based, 4) income-based, and 5) Driver’s License Classes. The breakdown of the age, gender, income groups, and driver’s licenses of the respondents are in **Table 7**, **Table 8**, **Table 9**, and **Table 10**, respectively. The income-based demographic was unique to this study and can be attributed to other underlying factors such as education level, overall general health, and home stability. Comparison to the Alberta population was conducted using Canada’s 2021 Census for Alberta (when statistics were available). The sample population skewed younger and more male than the general Alberta population. Both income and driver license type exhibited diversity in the sample population.

Table 7. Participants' age summary.

Age Group	Count	Percentage	Alberta Population*
All	454	100%	100%
Blank (Do Not Want to Specify)	33	7.3%	----
Less than 20	1	0.2%	7.3%
20-29	41	9.0%	15.3%
30-39	106	23.3%	19.3%
40-49	104	22.9%	17.1%
50-60	124	27.3%	15.7%
Over 60	45	9.9%	25.3%

* Of those aged 15 to 89

Table 8. Distribution of participants' reported gender.

Gender Response	Count	Percentage	Alberta Population*
Female	171	37.7%	50.3%
Male	270	59.5%	49.7%
Other/Do Not Want to Specify	13	2.8%	---
Total	454	100%	100%

* Of those aged 15 to 89

Table 9. Distribution of participants' reported income bracket.

Income Bracket	Count	Percentage
Less than $75,000	92	20.2%
$75,001 – $125,000	133	29.3%
Over $125,000	141	31.1%
Do Not Want to Specify	88	19.4%

Table 10. Driver's license classes.

License Class	Count	Percentage
Class 1	95	20.9%
Class 2	74	16.3%
Class 4	11	2.4%
Class 5 Non-GDL	226	49.8%
Class 5 GDL	42	9.3%
Class 6	1	0.2%
Class 7	2	0.4%
Other	3	0.7%

Regarding driver's licenses, Classes 1 through 4 pertain to industrial and commercial drivers, Class 5 is a general driver's license, Class 6 is motorcycle-only, and Class 7 is a learner's permit. Other responses were likely international licenses or no licenses. The licenses were regrouped into the following categories in **Table 11** for analysis purposes.

Table 11. Driver's license class categories.

License Class	Classes Combined	Count	Percentage
Commercial	1 to 4	180	39.6%
General	5 Non-GDL	226	49.8%
New/Other	5 GDL, 6, 7, Other	48	10.6%

4.2.2. Which Lighting Setup Stands Out the Most?

The first question of interest was determining which color lighting setup stood out the most in a side-by-side comparison. **Table 12** provides the response distribution for the group as a whole. From that table, it is clear that amber-white stood out of the three, while amber-blue stood out the least.

To explore how different demographics viewed the configurations, **Table 12** shows the age-based responses to this question. Age appeared to have played a role in determining which lighting setup was more conspicuous. Generally speaking, amber-blue was favored by younger respondents and trended downward with age. The reverse occurred with amber-white, where the older groups favored it. Interestingly, amber-only seemed to be consistent throughout all the age groups.

Aside from age, this question was also broken down by gender, and its response distribution is shown in **Table 12**. The gender-based analysis (GBA) showed that females did not find the amber-blue color setup the standout, but rather the amber-white setup. For males, the difference in preference was minimal between the three color combinations. Those who identified as 'other' or chose not to specify had a slight preference for amber-only.

Table 12. Gender-based, Income-based, Driver's License-based responses to "Which ONE of these lighting setups stands out the most to you?".

Groupings	Amber-Only	Amber-Blue	Amber-White
Whole Group Responses			
Total	35.2%	24.7%	40.1%
Age Group			
<20/Blank	29%	26%	44%
20-29	39%	41%	20%
30-39	39%	26%	35%
40-49	35%	29%	37%
50-60	33%	18%	49%
Over 60	36%	13%	51%
Gender Response			
Female	43.3%	10.5%	46.2%
Male	30.0%	33.3%	36.7%
Other/DNS	38.5%	30.8%	30.8%

Income Bracket			
Less than $75,000	36%	27%	37%
$75,001 – $125,000	35%	25%	41%
Over $125,000	36%	21%	43%
DNS	34%	28%	38%
License Class			
Commercial	32%	32%	36%
General	39%	18%	43%
New/Other	29%	27%	44%

Income was also explored to see if there was a correlation with lighting color perception. Amber-white was perceived as the standout for all income ranges, with amber-only coming in second. The difference in light-color preference for those making less than $75,000 annually and those not wanting to specify was slight compared to the other two groups. The data indicated that amber-blue had the lowest level of perception.

Finally, a comparative analysis was then conducted using the license groups. Commercial license holders viewed all lighting schemes equally, while those with a general or new license perceived that amber-white stood out the most, thus suggesting that a driver's skillset and level of training may have influenced their light color perception preferences.

A Chi-Square analysis was conducted on gender-, age-, income-, and license-based results to determine if the responses to the light colors and response groups were dependent or independent. **Table 13** summarizes the results.

The low p-values for the gender, age, and license groupings strongly suggest that their response behavior depended on their demographics, meaning that an individual's perception of lighting configurations correlated to their age, gender, and driving purpose and experience. However, the high p-value for income indicates that its correlation to lighting preference was weak. This lack of correlation was the case for other income-based analyses and thus was considered irrelevant. Other demographics considered but found irrelevant were corrective lenses and vehicle ownership.

Table 13. Age and Gender-based F-Test P-Values.

Groupings	F-Test P-Value
Age	0.02
Gender	4.4E-6
Income	0.86
Driver's License	0.02

4.2.3. Comfort passing a snowplow

One survey question aimed to see if a light color influenced the confidence or hesitancy for passing a snowplow. **Figure 5** illustrates a high level of discomfort in passing a snowplow regardless of the color scheme used. This discomfort may be due to the obscuring blowing snow or the snowplow's intimidating size rather than the snowplow's level of perceptibility. This consistently strong level of discomfort for the general population would suggest that it was the same regardless of demographics, and therefore, this detail was not considered.

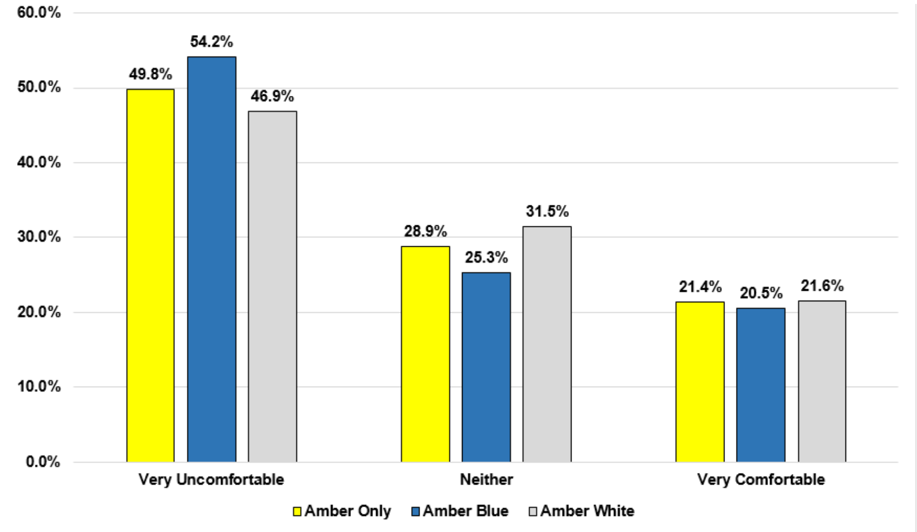

Figure 5. Response distribution to 'How comfortable would you be overtaking these snowplows based on their light configuration? Very uncomfortable to Very comfortable."

4.2.4. Pairwise comparisons of the lighting schemes

The next series of questions asked the participants to compare the different lighting configurations two at a time. This investigated the participants' direct preference by narrowing it down to a simple (A) or (B) preference choice. The original question was presented as a Likert 1-5 sliding bar scale, later simplified to a 3-level scale by combining Levels 1 and 2 together and 4 and 5 together. Similar to previous analyses, the data analysis was conducted, considering the differences among various demographics, such as age, gender, and income. **Table 14** displays the entire group's responses to each pairing.

Through the comparisons, an ordered preference emerged: amber-white was the favored setup, followed by amber-only, and finally, amber-blue. Further comparisons based on the age demographic were then investigated with the following results:

Table 14 reveals an interesting pattern where respondents under 40 did not prefer one configuration over another. However, with increasing age groups, a clear preference appeared following what was found for the whole group, with amber-white standing out the most and amber-blue the least.

Table 14. Group responses to pairwise comparisons.

	Amber Only vs. Amber-Blue			Amber Only vs Amber-White			Amber-White vs Amber-Blue		
Groupings	**Amber-Only**	**Amber-Blue**	**Neither**	**Amber-Only**	**Amber-White**	**Neither**	**Amber-White**	**Amber-Blue**	**Neither**
Whole Group Responses									
Total	53.5%	37.7%	8.8%	37.4%	49.3%	13.2%	52.4%	37.0%	10.6%
Age-Based Responses									
<20/Blank	56%	26%	18%	38%	38%	24%	44%	32%	24%
20-29	46%	46%	7%	49%	41%	10%	46%	49%	5%
30-39	52%	42%	7%	44%	45%	10%	44%	44%	11%
40-49	53%	38%	10%	41%	43%	15%	47%	40%	13%
50-60	53%	39%	8%	29%	57%	14%	58%	33%	9%
Over 60	64%	27%	9%	24%	67%	9%	80%	16%	4%
Gender-Based Responses									
Female	70%	27%	3%	48%	43%	9%	64%	29%	7%
Male	42%	45%	13%	30%	53%	16%	44%	43%	13%
Other/DNS	77%	15%	8%	46%	46%	8%	69%	31%	0%
License Based Responses									
Commercial	43%	46%	11%	33%	54%	13%	45%	42%	13%
General	62%	30%	8%	42%	45%	13%	59%	31%	10%
New/Other	54%	42%	4%	35%	52%	13%	48%	46%	6%

Similarly, gender also appeared to affect lighting scheme preference. In this demographic arrangement, a few key observations are noted. The preferences of females and males seem at odds with each other. The male population considered the amber-blue as equally comparable to either amber-only or amber-white, whereas the female and other/DNS populations did not view amber-blue as perceptible as the other two. Also, the female and other/DNS groups found that amber-only and amber-white were comparable, but males preferred amber-white to amber-only.

As suspected earlier, the participant's license was also correlated with their lighting choices. For a two-sample side-by-side comparison, commercial drivers perceived that the amber-blue light was comparable to the amber-only and amber-white setups. However, they found that amber-white stood out more than amber-only, possibly because of being on the road professionally and being more aware of flashing lights. The results from the other two categories of general and new/other followed the same preference trend seen in the other demographics, suggesting that the driver's license held by a participant will affect their perception of lighting colors.

4.3. Summary

Based on the field experiment and survey results analysis, amber-white was identified as the superior lighting scheme of the three options tested. Field tests showed amber-white and amber-blue were statistically identical as they had the lowest reaction times. Then, from the survey, when considering the group's preference and the demographic breakdown, amber-white was the most perceptible lighting combination for most participants. The second-best option depended on several factors, primarily demographics, as determined through the public surveys. Young male drivers viewed the amber-blue setup as more perceptible, while all other participant combinations favored the amber-white setup followed by amber-only. One key takeaway was that age, gender, and license class may have influenced the lighting configuration that an individual found more perceptible.

5. Conclusions

Inclement winter weather poses a significant risk to motorists as surface conditions deteriorate due to ice and snow. Transportation agencies and maintenance personnel use snowplows and other WRM equipment to clear the roads. However, these vehicles can be challenging to see due to snowfall, self-generated snow plumes, or snow plumes generated by passing motorists. A comprehensive study was designed and conducted using two methods to evaluate alternative lighting configurations on snowplows to identify ways to improve the visibility of WRM equipment.

5.1. Research Findings

The field experiment provided a numerical and scientifically repeatable study to quantitatively compare and evaluate the alternative lighting schemes to the current standard. This naturalistic field experiment focused exclusively on two specific alternative lighting schemes for WRM snowplow trucks during normal operations under winter conditions. Recordings from the deployments were used in a general public survey to expand the reach of the field experiment and gather input and opinions of the general populace of Alberta on how they perceived and compared the lights from the field experiment. Currently, the permitted standard in Alberta is amber-only, and the alternatives considered were amber-blue and amber-white. These two alternative colors were chosen for (1) white lighting is the most perceptible in literature, and (2) those in the maintenance industry requested blue lighting. The results from this experiment are as follows:

- Statistical analyses found that the mean reaction times were statistically shorter when using the amber-blue and amber-white lights than the current amber-only setup.
- Likewise, the variance in the reaction times was statistically smaller for the amber-blue and amber-white over amber-only.
- The performance between amber-blue and amber-white was not statistically different for the mean or variance, suggesting that using a single color does not perform as well as using two colors on a lighting setup.
- The survey results overwhelmingly showed that most of the population found that amber-white stood out the most, followed by amber-only and amber-blue. These differences were very highly impacted by age, gender, and license class held.

Overall, based on the results from this project, it can be stated that the amber-white setup is the most effective at bringing attention to the vehicle. However, as both Michigan's and Missouri's DOT studies mentioned, white can sometimes be too bright and uncomfortable to see and cause glares, especially at night (Brown, et al. 2018, Zockaie, et al. 2020), or may not be preferred by all people.

5.2. Limitations and Future Work

In conducting this study, a number of external factors imposed constraints on the methodology, necessitating adjustments to the research approach. The winter of 2021/2022 brought unseasonably warm weather, leading to delays in field experiments, while freezing rain events posed significant safety concerns. Additionally, the COVID-19 pandemic further complicated the study, affecting volunteer availability furthering delays in data collection and analysis. These challenges were met with flexible and pragmatic solutions to ensure the continuation of data collection. Within this context, the study has identified several specific limitations:

- The experiment was conducted only in the daytime, where bright sunlight, even when obscured by clouds, compromised the perceived brightness of the implemented lighting setups. This choice was intentional, as most collisions involving snowplows in the region occurred during daylight hours.

- The study used larger semi-tractor trailer-based snowplow trucks and did not include smaller support vehicles.
- The chase vehicles used were intermediate-sized SUVs and half-ton pickup trucks and did not include shorter vehicles, such as compact cars or sedans. The shorter driving position of these smaller cars may affect the results.
- Some participants mentioned that the more elevated lights were considerably clearer. Therefore, performance results may change when the same lights are installed on shorter vehicles.
- Another limitation was that this study only considered adding blue and white lights to the amber setup and no other colors (e.g., green, purple, or red).
- The survey questions were focused on direct comparisons between the three lighting setups via an online survey, where external factors could not be accounted for. It is recommended that a survey be conducted in person whereby equipment used to view the videos and images is consistent.

Given these limitations, several avenues for future studies are evident. Lighting elevation could be studied to see if elevating the lights could drastically improve the visibility of trucks, regardless of light colors. Examining performance differences under night-time conditions with much greater lighting contrasts would also be valuable, considering that distinct colors are perceived differently depending on the ambient light level. Furthermore, repeating this study with other colors, such as green, red, or purple, along with the blue and white lights, may better show if the improvement in the perceptibility of the snowplows relates to a specific color or just any additional color. The success of green lighting in other U.S. states, due to its visual comfort and minimal glare, suggests it could be beneficial for winter use when green in not prevalent in the environment during the winter months, especially around snow cover.

Nevertheless, this study has provided critical insights into the evaluation of lighting configurations for winter road maintenance vehicles, establishing a foundation for improved road safety practices in adverse weather conditions.

Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

Author's Note: This study was done to the high ethical standards set forth in academic research in accordance with the conditions outlined in the University of Alberta's ethics review board, Alberta Research Information Services (ARISE). Two ethics reviews were conducted and approved for each part that involved human participants.

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