PAPER #14: REAR LIGHTING CONFIGURATIONS FOR WINTER MAINTENANCE VEHICLES

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ABSTRACT

Winter maintenance vehicles for snowplowing often operate when visibility is compromised. Rear lighting on snowplows serves two purposes: to alert drivers of nearby vehicles that the snowplow is on the roadway, and to provide cues to those drivers about the snowplow's relative speed and distance. Flashing and strobing lights have been used on snowplows by many departments of transportation, who consider these lights as having high conspicuity and attention-getting properties. However, most accidents involving snowplows are rear-end collisions by other vehicles, and previous research supports the idea that flashing or strobing configurations are less effective than steady-burning lights at providing cues about relative speed, distance and closure to drivers approaching a snowplow from behind. To test this concept, a prototype steady-burning light bar using light-emitting diodes was developed and tested on a snowplow vehicle, which was also equipped with conventional flashing lights. The ability of subjects following snowplows to detect deceleration of the snowplow was measured with each lighting configuration during nighttime field tests conducted while snow was falling. The mean time to detect closure was significantly shorter with the steady-burning light bar than with flashing lights. Subjective ratings of visibility and confidence for judging speed and distance were also higher with a steady-burning light bar than for the conventional system. The prototype light bar configuration could easily be adapted to existing snowplow vehicles as a retrofit, or it could be incorporated into specifications for new maintenance vehicles.

BACKGROUND

A major problem experienced by snowplow operators is the inability of other vehicle drivers to maneuver safely near the snowplow. Around 70% of all accidents involving snowplows involve collisions into the rear of snowplow trucks.[1,2] On the surface, the solution to this problem seems to be one of increasing the conspicuity of the snowplowing vehicle. While conspicuity is indeed important, equally important is improving the ability of other drivers to judge the distance, direction and speed of the snowplow relative to their own vehicles, especially in a driving environment where falling snow, oncoming headlights and other flashing signals can contribute to glare and fatigue.[3]

Rear lighting on snowplow vehicles should serve two distinct purposes:

- Provide a conspicuous signal to other drivers that the plow is on the road
- Provide cues about the plow's operating speed, direction and distance, relative to other vehicles

Lighting systems that are highly conspicuous (e.g., strobe lights) are often poor at providing speed and distance cues, and vice versa. The challenge of rear lighting and signaling for snowplows is finding an effective balance between these purposes.

Review of the relevant literature on rear lighting and signaling shows that several factors affect visibility of a vehicle to other drivers:

- Mounting location[4]
- Temporal light characteristics[5-8]
- Spatial light characteristics[9,10]
- Luminous intensity[11]

Significant cloud accumulation behind the truck can occur while plowing snow. The most effective mounting location for rear lights in this case is as high as possible in order to ensure that the lights will clear the cloud behind the truck. A number of agencies in the U.S. and Canada specify high mounting locations for rear lights, including the Department of Transportation in New York State and the Ontario Ministry of Transport. Such specifications are in general agreement with the recommendations of Marsh.[4] In addition, a high mounting location permits the maximum lamp intensity to be visible from the furthest distance away from the plow truck. As a following vehicle approaches the plow truck, the angle between the maximum intensity from the lamp and the driver's view of the source increases, and the intensity toward the following driver decreases, reducing potential for glare.

Flashing lights will be perceived as having higher brightness than steady-burning lights, up to a flash frequency of about 15 flashes per second.[5] Such brightness enhancement can aid in conspicuity, and several rear lighting systems have been designed to have a flash rate between 5 and 9 flashes per second in order to maximize their perceived brightness.[12] While conspicuity may be greater with such configurations, an observer's ability to make accurate judgments of relative speed or distance may be compromised when flashing or strobing lights are used. Croft[6] observed that the judgments required in tracking an object were difficult to make under strobing conditions, yet very easy in steady-lighting conditions. Observations made during a study of service vehicle lighting for maintenance operations[7] similarly pointed out that strobing and flashing systems designed for maximum conspicuity can at the same time reduce one's ability to judge relative speed and distance. Periodic sampling of the field of view in another study resulted in deterioration of one's motion-tracking ability that increased as the distance to the object of interest decreased.[8]

As for spatial characteristics, an investigation of rear lighting packages on vehicles[9] found that one's ability to accurately estimate relative speed and distance depended also on the spatial extent (size) of the signal system. A single light source provided very poor speed and distance information, while an extended spatial array of sources provided good cues for speed and distance. Changes in apparent size are critical to time-of-arrival judgments,[10] so larger-sized stimuli should be more effective in making such judgments. An approach that involved the use of floodlights to "wash" the rear of a snowplow with light was somewhat effective at night during clear conditions but appeared to be much less effective during inclement weather[9] because of the much-reduced intensity.

In order to investigate the properties of different rear lighting configurations, several types were mounted on snowplow vehicles and evaluated first in a simple demonstration using subjective ratings, and later in field tests conducted on highways during winter storms at night.

METHOD: SUBJECTIVE EVALUATIONS

Preliminary field demonstrations of several rear lighting configurations were conducted during the winter of 1997/1998. Four configurations were tested on county snowplow trucks in upstate New York:

- Conventional configuration: The typical flashing amber lighting configuration used on snowplow trucks in New York State.
- Indirect edge delineation: An indirect edge delineation system similar in concept to the floodlight approach used by Stout *et al*.[11] but designed to illuminate the left- and right-hand edges of the rear of the snowplow truck only.
- Alternating high-mounted: A temporally alternating, high-mounted configuration of two pairs (one amber and one red) of flashing lamps configured so that at all times, either the yellow or the red pair was on. From a distance, this configuration appeared to be two steady-burning points of light that alternated in color between amber and red.
- LED light bar configuration: A horizontal light bar arrangement using light-emitting diodes (LEDs) in a steady-burning configuration. Commercially available LED turn signal units were assembled to form the light bar.

The luminances of the amber lamps in the standard configuration and the alternating high-mounted configuration were measured in the field to be approximately 60,000 to 90,000 cd/m^2. The red lamps in the alternating high-mounted configuration had a luminance of approximately 13,000 to 15,000 cd/m^2. Because red lights are higher in perceived brightness than yellow lights of the same luminance,[13-16] the brightness differences between the yellow and red lamps was smaller than their luminances imply. Luminances of truck surfaces illuminated by the indirect edge delineation configuration ranged from 160 to 290 cd/m^2. Luminance measurements of the LED light bar were more difficult to measure because the LED units that were used formed arrays of point sources too small to accurately measure with a luminance meter. Spatially-averaged luminances of arrays ranged from about 25,000 to 50,000 cd/m^2; the luminance of individual luminous point were significantly higher.

Using a simple questionnaire, county snowplow operators were asked to rate the visibility of each lighting system and to rate the confidence with which they would be willing to pass the snowplow from behind. Each of the ratings were made on a scale of -3 (worst) to +3 (best). Ratings were made at night for both clear weather conditions and heavy snow conditions. Six snowplow operators made subjective judgments of all four lighting configurations. Every operator provided ratings for both weather conditions.

RESULTS: SUBJECTIVE EVALUATIONS

The mean visibility and confidence ratings (and standard deviations) are listed in Table 1. As expected, the ratings were worse for the heavy snow conditions than for the clear conditions. Using within-subjects analyses of variance (Table 2), the type of lighting configuration had a statistically significant impact on ratings of visibility and confidence ($p<0.05$), and the ambient weather condition had a significant effect on ratings of visibility and confidence ($p<0.05$). There was a statistically significant ($p<0.05$) interaction between lighting configurations and weather conditions for the confidence ratings, but not for the visibility ratings. Because the LED light bar configuration resulted in the highest subjective ratings of visibility and confidence among all of the configurations, a modified version of this configuration was selected for comparison in field tests during the following winter.

METHOD: CLOSURE DETECTION TEST

Based on the preliminary findings from the subjective evaluations, an amber light bar configuration using an array of LED marker lights was developed for field tests in upstate New York during the 1998/1999 winter (see Figures 1 and 2). The LED units used in the light bars were oblong, 7 by 3 in. (18 by 8 cm) devices each with 26 high-output amber LEDs. The devices meet Society for Automotive Engineers (SAE) specifications[17] for amber mid-turn units used on commercial trucks, but were not used for the purpose of turn signaling in this study. Two light bars were developed for use in a vertical orientation on the snowplow trucks; one on each side of the truck, in order to provide information to other drivers about the width of the snowplow truck. In addition, the horizontal orientation studied earlier was found to be impractical for some truck configurations because of protrusions associated with the storage of salt for spreading on roads. The light bars were designed as retrofit units mounted onto the rear of an existing snowplow truck, and were used in conjunction with airfoils designed to help keep the rear of the truck clear of snow buildup.[18,19]

Because of the previous literature on flashing light configurations and their potential impacts of such configurations on judgments of relative speed and distance, [6,7] it was hypothesized that the steady-burning light bar configuration would result in improved judgments relative to the flashing light configuration. A field study to investigate this hypothesis was designed with several constraints in mind:

- The study should use equipment and vehicles used during actual snowplowing operations on the road.
- The study should interfere minimally with snowplowing operations.
- Differences in location, weather and ambient light level should be minimized when comparing the alternative lighting configurations.

A single snowplow truck was fitted with both lighting configurations. A closure detection test was developed whereby a subject rode in the passenger seat of a vehicle that was operated at a constant speed (30 mph) and started a fixed distance [100 m; measured using a lidar (*li*ght *d*etection *a*nd *r*anging) range finder] behind a snowplow truck also moving at the same speed. After a random interval ranging from 20 to 60 sec, an experimenter riding in the snowplow silently signaled to the snowplow operator to decelerate by slowly taking pressure off the accelerator pedal, but without pressing the brake pedal (which would illuminate the truck's brake lights). At the same time the experimenter would start a stopwatch. The subject, who was in cell telephone contact with the experimenter, was instructed to say "Now!" when certain that the following vehicle was beginning to approach the snowplow. The experimenter would stop the stopwatch, record the time, and prepare for the next trial. For each trial, the rear lighting configuration was switched from inside the snowplow cab between the conventional flashing lights and the steady-burning light bars (the first lighting configuration seen in each session also alternated). Twelve trials were conducted during each subject's session, six for each lighting configuration. Large sample sizes were not easily obtainable in the study because actual winter maintenance vehicles were used during plowing operations.

All of the sessions were conducted in one night during the same snowstorm, while the snowplow operator plowed snow and spread abrasive along a several-kilometer circuit on an interstate highway. In this way, the ambient weather and lighting conditions were kept as constant as possible. Three adult subjects with New York State driver's licenses participated in the study; one of these subjects finished two sessions before the study was completed at the end of the night when the snowplow truck returned to its station to refuel. Therefore, a total of 48 trials were conducted; 24 for each lighting configuration.

RESULTS: CLOSURE DETECTION TEST

Figure 3 shows the mean closure detection times for all trials and the mean of the standard deviations for each subject; times for each subject are summarized in Table 3. Using a one-tailed Student's t-test comparing the raw closure detection times for each configuration, the mean closure detection time with the light bar configuration (9.8 sec) was found to be statistically significantly shorter ($p<0.05$) than with the flashing light configuration (12.4 sec).

DISCUSSION AND CONCLUSIONS

Although flashing and strobing lights have been used by several winter maintenance agencies to provide high conspicuity of the snowplow vehicle, previous research indicates that such sources are less effective than steady-burning lights for estimating relative speed, distance and closure.[6,7] Furthermore, an array of such lights subtending the width of the snowplow vehicle will be more effective than a single light source.[9] Based on these previous findings, the results of subjective evaluations of several rear lighting configurations on snowplow vehicles showed that a steady-burning light bar resulted in the highest ratings of visibility and of confidence for passing. When employed in a field study on highways during actual snowplow operations, the light bars resulted in shorter closure detection times than a configuration using flashing lights. The light bar was a retrofit solution that was easily mounted onto the snowplow (Figure 2), and could be incorporated into the truck through future specifications. The results from the investigations presented here, however, are not sufficient to provide estimates of the relative impact of location or flash rate; rather, they are comparisons between two specific configurations as tested in the field.

The 2.6 sec closure detection time improvement found in the present study using the light bar configuration seems small compared to the overall 10-to-12-sec closure detection times that were measured, but even at speeds of 30 mph, 2.6 sec corresponds to a driving distance of 35 m. As pavement conditions are much different during winter storms than under clear weather conditions and likely to have even longer stopping sight distances,[20] the shortened response time may give drivers of other vehicles enough driving distance to safely maneuver in the vicinity of the snowplow.

The steady-burning light bar configuration used in the present study could possibly be combined with a dynamic but non-flashing component, located similarly as currently existing flashing lights. Such a component could be linked to the snowplow vehicle's transmission to display or graphically represent the snowplow's speed or direction of travel. Its dynamic nature would increase its conspicuity[5] but perhaps not impair judgments of relative speed and distance.

The use of LEDs in the light bars also results in reduced power requirements relative to conventional incandescent sources. The amber LED units used in the light bar in Figure 1 are approximately 6 W each; in comparison, incandescent lamps with similar distributions are about 27 W. The amber lamps used in the conventional rear lighting configuration were 35 W each. Because LEDs are low-power devices, are relatively durable and are becoming more and more cost-effective for signage and signaling applications,[21] they appear to be promising technologies for rear lighting and have been demonstrated to provide adequate visibility and closure detection during inclement weather. They also have less demand on the electrical system of the snowplow truck. No blockage of the light bar by snow or ice was experienced during field demonstrations; the use of airfoils [18,19] described above will also help to keep rear surfaces clear of snow and ice accumulation.

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Figure 1. Schematic diagram of vertical LED light bar configuration. All dimensions are in inches.

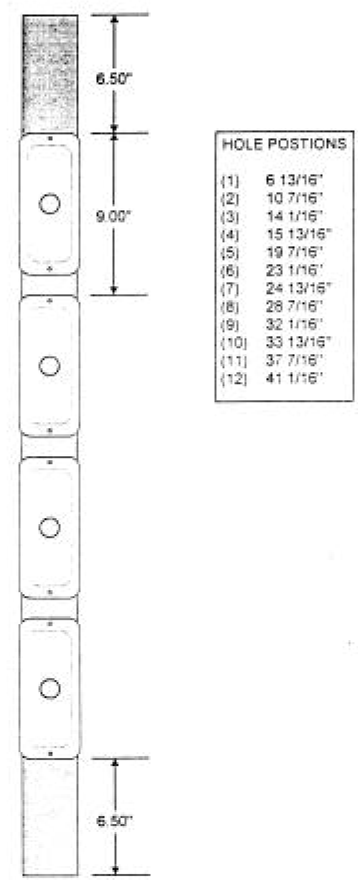

Figure 2. Rear of snowplow truck showing light bars and conventional flashing lights.

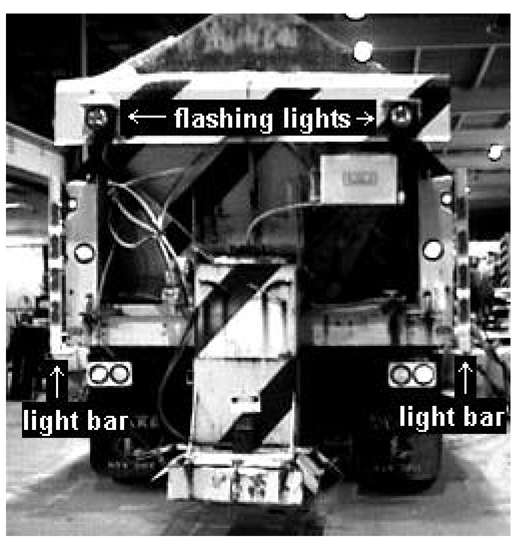

Figure 3. Mean closure detection times and mean standard deviation for each subject, for the conventional and light bar configurations.

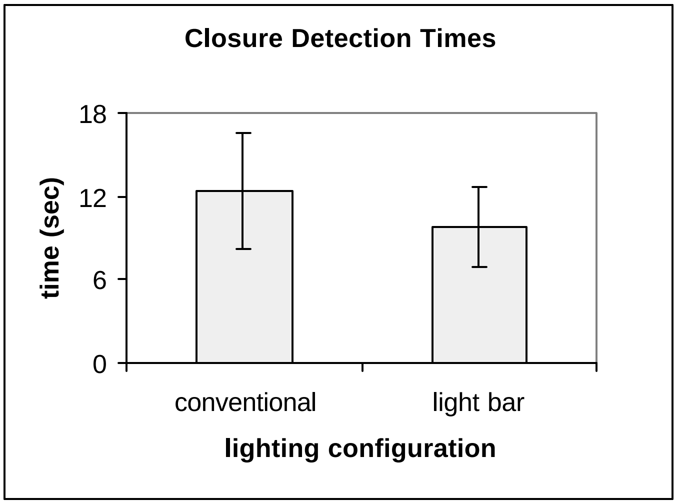

Table 1. Mean ratings of visibility and confidence for rear lighting configurations and standard deviations, for clear and heavy snowing conditions.

Configuration	**Ambient condition**	**Visibility rating** ***(standard deviation)***	**Confidence rating** ***(standard deviation)***
conventional configuration	clear	0.00 *(0.89)*	+0.50 *(1.05)*
conventional configuration	heavy snow	-0.33 *(0.82)*	-1.83 *(1.17)*
indirect edge delineation	clear	-0.33 *(1.03)*	+0.33 *(1.21)*
indirect edge delineation	heavy snow	-0.50 *(1.64)*	-0.33 *(1.03)*
alternating high-mounted	clear	+2.00 *(1.26)*	0.00 *(1.26)*
alternating high-mounted	heavy snow	+1.33 *(0.82)*	-1.33 *(1.21)*
LED light bar	clear	+3.00 *(0.00)*	+1.17 *(0.75)*
LED light bar	heavy snow	+2.33 *(0.82)*	+0.17 *(1.17)*

Table 2. Summary tables for within-subjects analyses of variance (ANOVAs) for the (a) visibility and (b) confidence ratings.

a. ANOVA Summary: Visibility Ratings

Source of variation	**SS**	**df**	**MS**	**F**
between subjects	27.7	5		
weather	2.52	1	2.52	14.8*
lighting	78.9	3	26.3	45.3*
weather × lighting	0.56	3	0.19	0.79
weather × subjects	0.85	5	0.17	
lighting × subjects	8.73	15	0.58	
weather × lighting × subjects	3.57	15	0.24	
total	122.8	47		

*Statistically significant at the p<0.05 level.

b. ANOVA Summary: Confidence Ratings

Source of variation	**SS**	**df**	**MS**	**F**
between subjects	39.9	5		
weather	21.3	1	21.3	118.5*
lighting	14.7	3	4.89	11.9*
weather × lighting	4.67	3	1.56	7.43*
weather × subjects	0.92	5	0.18	
lighting × subjects	6.08	15	0.41	
weather × lighting × subjects	3.08	15	0.21	
total	90.7	47		

*Statistically significant at the p<0.05 level.

Table 3. Mean closure detection times and standard deviations, for each subject.

Subject	**Conventional configuration**		**Light bar configuration**	
	Mean closure detection time (sec)	**Standard deviation**	**Mean closure detection time (sec)**	**Standard deviation**
1	9.7	3.0	6.8	1.5
2	11.3	4.5	8.5	2.1
3	14.3	5.0	12.1	5.0