Maximizing the Conspicuity of Maintenance Vehicles

Synthesis Report

CLEAR ROADS

research for winter highway maintenance

CTC & Associates LLC

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16. Abstract

Maximizing the conspicuity of state department of transportation (DOT) fleet vehicles and equipment used for summer and winter maintenance is expected to improve highway safety and increase mobility for both the motoring public and the vehicle or equipment operator.

This synthesis sought to build on the October 2015 Clear Roads report *Use of Equipment Lighting During Snowplow Operations*. A review of domestic and international research and other relevant resources gathered information about the lighting, paint colors and retroreflective taping patterns used to enhance the conspicuity of state DOT maintenance vehicles and equipment. The literature search also sought information about the practices used to enhance the conspicuity of vehicles used at airports, for emergency purposes and by law enforcement, and investigated how lighting, color and retroreflective markings can improve general vehicle conspicuity. The report concludes with a brief examination of the use of high-visibility garments to improve pedestrian and worker safety.

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Executive Summary

Maximizing the conspicuity of state department of transportation (DOT) fleet vehicles and equipment used for summer and winter maintenance is expected to improve highway safety and increase mobility for both the motoring public and the vehicle or equipment operator.

Building on the October 2015 Clear Roads report *Use of Equipment Lighting During Snowplow Operations*, this synthesis report reviews domestic and international research and other relevant resources that examine the lighting, paint colors and retroreflective taping patterns used to enhance the conspicuity of state DOT maintenance vehicles and equipment.

This synthesis report also reviews the literature on practices used to enhance the conspicuity of vehicles employed at airports, for emergency purposes and by law enforcement, as well as the lighting, color and retroreflective markings used to enhance general vehicle conspicuity. The report concludes with a brief examination of the use of high-visibility garments to improve pedestrian and worker safety.

The summary tables below organize information appearing throughout this synthesis report into three categories of conspicuity practices:

- Vehicle lighting.
- Vehicle color.
- Retroreflective and other markings.

The tables provide brief descriptions of the conspicuity-related findings and practices identified in the literature search. The column labeled “For More Information” provides the page number where a discussion of each finding or practice begins in this report.

Vehicle Lighting

The tables below present information associated with vehicle lighting in three topic areas:

- Research related to winter maintenance equipment.
- Practices related to winter maintenance equipment.
- Research and practices related to various vehicle types.

Vehicle Lighting Research: Winter Maintenance Equipment

Agency/Source (Year)	Description of Finding	For More Information
TRB 96th Annual Meeting Compendium of Papers (2017)	Field tests were conducted to assess proposed lighting and marking standard for snow maintenance equipment, subsequently published as a national guideline by the Transportation Association of Canada (see the citation below).	9
Transportation Association of Canada (2015)	Guidelines appearing in the Snow Removal Equipment Visibility Guide, the product of a research project initiated by the Ministry of Transportation of Ontario, call for: • Using amber and blue light-emitting diode (LED) lights on the side	10

Vehicle Lighting Research: Winter Maintenance Equipment		
Agency/Source (Year)	**Description of Finding**	**For More Information**
	and top of the rear box on the plow truck. • Maintaining the amber light as steady burning, with the blue light flashing on and off. • Using automatic dimmers for day and night. Related resources include a 2015 article and peer exchange presentation that highlight the research that resulted in the updated equipment standards presented in the visibility guide.	
Clear Roads Pooled Fund Study (2015)	A literature search and surveys were used to develop a series of best practices. Among the findings: • Amber is the most commonly used color for warning lights. • LED lights are favored for use in new vehicles. • Flashing and steady burning lights should be used with day and night settings.	12
Center for Transportation Studies, University of Minnesota (2013)	Researchers recommend the use of vertical bar lights with steady burning lights flanked by black bars. This configuration was found to: • Improve drivers' detection of approach under low-contrast conditions. • Allow drivers following a snowplow in a simulator to respond faster.	13
TRB 90th Annual Meeting Compendium of Papers (2011)	Pairs of LED warning beacons provided closure distances equivalent to those provided by conventional rotating beacons while using substantially less power.	24
Nevada DOT (2008)	Researchers' recommendations and findings include: • Placement of an LED light bar on both sides of the snowplow, with some lights set to steady burn and others flashing. • Placement of a light bar on top of the sander. • A preference for narrow-beam lamps complemented with high-intensity discharge systems.	14
Minnesota DOT (2008)	A project examining the effectiveness of LED lights found that: • LED lights are comparable in conspicuity to standard strobe lights under specific conditions. • A standard strobe outperforms an LED light when viewed from angles other than from a vehicle approaching the rear of the snowplow.	15

Vehicle Lighting Practices: Winter Maintenance Equipment

Agency (Year)	Description of Practice	For More Information
Idaho Transportation Department (2015)	The agency changed from flashing yellow to flashing red rear lights; the change appears to have resulted in fewer crashes.	15
Iowa DOT (2015)	A pilot project places rear-facing white and blue lights on the vehicle in addition to amber warning lights. (A legislative and DOT review of the pilot, which ends in 2018, will determine further implementation.)	16
Michigan DOT (2016)	• The agency and selected municipalities will use green and amber lights (flashing, rotating or oscillating) on a portion of their fleets in an effort to reduce crashes. • The agency-developed Superior Stick lighting system attaches to the end of wing plows and will extend and retract along with the wing plow blade.	17
Minnesota DOT (2011)	Agency guidelines indicate that blue lights may be used on snow removal and other equipment on the passenger side only (no more than 50 percent of the light bar may be blue).	18
Missouri DOT (2015)	An Innovations Showcase publication notes that LED lights improve visibility and reduce operator eye fatigue.	18
Ohio DOT (2012)	• As a result of a September 2012 state law, the agency started using an amber, green and white color combination, all with different pulses. (Studies suggest green lights are more easily detected by the human eye than other colors.) • Ohio is among the first states to use multiple colored lights, and is the first to use green lights.	19
Saskatchewan Ministry of Highways and Infrastructure (2015)	A fact sheet describes the agency's use of blue and amber lights beginning in December 2015 (consistent with the Transportation Association of Canada guidelines).	20

Vehicle Lighting Research and Practices: Various Vehicle Types

Agency/Source (Year)	Vehicle Type	Description of Finding or Practice	For More Information
National Cooperative Highway Research Program (NCHRP) (Proposed)	Maintenance	This proposed project will develop guidelines for adoption by the American Association of State Highway and Transportation Officials (AASHTO) for lighting, vehicle color and markings to identify transportation agency vehicles and equipment.	20
NCHRP (2008)	Maintenance	This document provides guidelines for the selection of warning lights on roadway operations equipment.	21
Indiana DOT (2008)	Maintenance	A project to identify more effective lighting concluded: • LED lights are preferred.	21

Vehicle Lighting Research and Practices: Various Vehicle Types			
Agency/Source (Year)	**Vehicle Type**	**Description of Finding or Practice**	**For More Information**
		• Amber is the clear color preference across all color configurations; second choice is bright blue. • Larger lights are more visible than smaller lights.	
Kentucky Transportation Cabinet (2015)	Maintenance	A survey assessed warning light practices in the U.S.; all 16 survey respondents use amber and LED light sources. Recommendations include using: • Amber and white for all work vehicle warning lights. • A slow flashing pattern. • Different intensities for LED lights during daytime and nighttime conditions.	22
Missouri DOT (undated)	Maintenance	The agency's fleet lighting guidelines recommend: • Installing beacons or mini-light bars at the highest point possible. • Using a dimmer function for LED lights and other higher-intensity lighting used at night.	24
Federal Aviation Administration (2010)	Airport	This advisory circular indicates that the standard for identification lighting is a yellow flashing light mounted on the uppermost part of the vehicle structure.	25
Applied Ergonomics (2014)	Emergency	An investigation of how to improve emergency vehicle lighting concluded: • A 4 Hz flash rate conveys greater urgency than a 1 Hz rate. • A 4 Hz single-pulse condition was associated with study participants leaving significantly more space before pulling out in front of an approaching police car.	27
Transportation Lighting Alliance (2016)	Passenger	Adaptive driving beam (ADB) headlight systems can offer safety benefits. (ADB systems detect oncoming headlights and reduce their intensity only in the direction of other lights.)	28
U.S. Department of Homeland Security et al. (2008)	Emergency, Law Enforcement, Maintenance	An experiment and findings from a literature search resulted in these recommendations: • Use different intensity levels for day and night. • Make more use of blue lights overall, day and night. • Use color coding to indicate whether or not vehicles are blocking the path of traffic.	28
Driving Magazine (2011)	Passenger	This magazine article describes three types of "eye disability" that result from glare, and addresses how the	29

Vehicle Lighting Research and Practices: Various Vehicle Types			
Agency/Source (Year)	**Vehicle Type**	**Description of Finding or Practice**	**For More Information**
		improper use of LEDs in passenger vehicles can cause these "disabilities" to occur.	

Vehicle Color

The table below summarizes findings on how vehicle color impacts conspicuity.

Vehicle Color Research: Various Vehicle Types			
Agency/Source (Year)	**Vehicle Type**	**Description of Finding**	**For More Information**
NCHRP (Proposed)	Maintenance	This proposed project will develop guidelines for adoption by AASHTO for lighting, vehicle color and markings to identify transportation agency vehicles and equipment.	20
Federal Aviation Administration (2010)	Airport	This advisory circular indicates that a yellowish-green color provides optimum visibility during all light levels.	25
National Highway Traffic Safety Administration (2017)	Emergency	This review of warning lights for EMS vehicles also noted that a lime-green vehicle color has the maximum conspicuity.	25
Federal Emergency Management Agency (2009)	Emergency, Law Enforcement	This report recommends using contrasting colors to help drivers locate a hazard amid the visual clutter of the roadway. (The specific color choice with respect to fluorescents may or may not be important, perhaps depending on background characteristics.)	27
Kansas DOT (2015)	Passenger	Researchers investigated how long it took study participants to identify approaching vehicles based on vehicle color and differing conditions. Despite differing lighting conditions where some colors were slightly more recognizable, the difference was not uniformly significant.	29
Proceedings of the National Academy of Sciences (2017)	Taxi	Singapore researchers reported that yellow taxis had 6.1 fewer accidents per 1,000 taxis per month than blue taxis, a 9 percent reduction in accident probability.	30

Retroreflective and Other Markings

The tables below summarize research and practices with respect to the use of retroreflective and other types of markings to enhance the conspicuity of vehicles. An additional table reviews the use of retroreflective materials in garments to improve pedestrian and worker safety.

Retroreflective and Other Markings Research and Practices: Various Vehicle Types			
Agency/Source (Year)	**Vehicle Type**	**Description of Finding or Practice**	**For More Information**
Transportation Association of Canada (2015)	Winter Maintenance	Guidelines appearing in the Snow Removal Equipment Visibility Guide call for: • Fluorescent yellow-green and black conspicuity panel on the back of the plow truck. • Red and white tape outlining the rear box.	10
NCHRP (Proposed)	Maintenance	This proposed project will develop guidelines for adoption by AASHTO for lighting, vehicle color and markings to identify transportation agency vehicles and equipment.	20
Mid-America Transportation Center (2010)	Maintenance	Researchers recommend red and white checkerboard markings for the rear of vehicle-mounted attenuators in work zones.	23
Federal Aviation Administration (2010)	Airport	This advisory circular recommends a minimum 8-inch-wide horizontal band of high-gloss white paint or white reflective tape around the vehicle's surface.	25
National Highway Traffic Safety Administration (2017)	Emergency	A review of emergency warning lights recommends a fluorescent, outward-downward chevron pattern of retroreflective sheeting on the back of the vehicle.	25
Federal Emergency Management Agency (2014)	Emergency, Law Enforcement	This report highlighting a range of research studies recommends: • Outlining vehicle boundaries with “contour” or “edge” markings using retroreflective material. • Concentrating retroreflective material lower on emergency vehicles to optimize interaction with approaching vehicles’ headlamps. • Using fluorescent retroreflective materials, especially yellow and orange, which have superior conspicuity properties and are particularly useful when a high degree of daytime visibility is desired.	26
Intertraffic World (2010)	Unspecified	This journal article describes full cube prisms, which eliminate the dead spots on the edges of the prism, and may result in better management of reflected light “to meet the observation and entrance angles of specific driver/vehicle types.”	30
Proceedings of the 5th International Driving Symposium on Human Factors in Driver Assessment and Vehicle Design (2009)	Unspecified	Ten small patches of retroreflective material were evaluated to quantify the effect of changing the coefficient of retroreflection on brightness perception.	30

Retroreflective and Other Markings Research and Practices: Various Vehicle Types

Agency/Source (Year)	Vehicle Type	Description of Finding or Practice	For More Information
TRB 96th Annual Meeting Compendium of Papers (2017)	Trucks	Study results indicate that the most visible retroreflective tape pattern is "the red and yellow combination of retroreflective tape placed horizontally and vertically on both right and left and upper and lower rear section of trucks."	31
Journal of the Australasian College of Road Safety (2014)	Trucks	This journal article refers to the United Nations Economic Commission for Europe (UNECE) 104 regulation for best practices in vehicle marking. The regulation allows for the use of red, white and yellow tapes.	31
Australasian Road Safety Research, Policing and Education Conference (2012)	Trucks	This presentation reviews the global perspective on the use of retroreflective materials.	32
5th Australian Road Engineering and Maintenance Conference (2010)	Maintenance, Trucks	The author of this conference presentation recommends that heavy vehicle operators follow the UNECE 104 regulation for vehicle marking.	33

Retroreflectivity in Garments Research and Practices

Agency/Source (Year)	User Type	Description of Finding or Practice	For More Information
Human Factors: The Journal of the Human Factors and Ergonomics Society (2016)	Pedestrians	Researchers found that garments with both electroluminescent panels and retroreflective materials yielded longer response distances than a retroreflective-only garment.	33
American Traffic Safety Services Association (2009)	Work Zone Crews	This pocket guide outlines the type of high-visibility apparel recommended for use in work zones.	34
Industry Affiliation Program for Human Factors in Transportation Safety (2007)	Pedestrians	Findings from a daytime field study include: • The amount of background material and season significantly affected the detection distance of a pedestrian wearing a fluorescent-colored garment. • Color contrast with natural backgrounds might contribute more to the conspicuity of fluorescent red-orange garments than does the corresponding luminance contrast. • Luminance contrast might contribute more to the conspicuity of fluorescent yellow-green garments than does color contrast.	34

Conclusion

The literature search conducted for this project uncovered a wide range of resources—from research results to agency practices and association guidelines—that consider products and practices to enhance vehicle conspicuity across a range of vehicle types and purposes. While the findings uncovered some common themes (for example, many agencies use amber lights or a combination of different color lights), we did not identify a clear consensus or a single set of best practices with regard to the use of lighting, vehicle color and retroreflective markings to enhance the conspicuity of maintenance vehicles.

This snapshot of recent research and current practices can assist agencies contemplating a modification of conspicuity-related practices. The findings presented in this report may provide agencies with support for a change under consideration, or may help agencies identify a new approach that may yield better results.

1 Introduction

Maximizing the conspicuity of state department of transportation (DOT) fleet vehicles and equipment used for summer and winter maintenance is expected to improve highway safety and increase mobility for both the motoring public and the vehicle or equipment operator.

For this synthesis, we reviewed domestic and international research and other relevant resources that address the lighting, paint colors and retroreflective taping patterns used to enhance the conspicuity of state DOT maintenance vehicles and equipment. We also gathered information about the practices used to enhance the conspicuity of vehicles used at airports, for emergency purposes and by law enforcement, and investigated how lighting, color and retroreflective markings can improve general vehicle conspicuity. This report concludes with a brief examination of the use of high-visibility garments to improve pedestrian and worker safety.

This synthesis seeks to build on the October 2015 Clear Roads report *Use of Equipment Lighting During Snowplow Operations*. Unless otherwise specified, the citations presented in this synthesis report are from U.S. sources. When applicable, citations are categorized and labeled as "Domestic Resources" and "International Resources."

2 State DOT Vehicles and Equipment

Publications addressing the conspicuity of state DOT fleet vehicles and equipment are presented separately below. Winter maintenance equipment is addressed first, followed by other types of vehicles and equipment.

2.1 Winter Maintenance Equipment

Among the most significant resources dealing with winter maintenance equipment conspicuity is the 2015 Transportation Association of Canada (TAC) Snow Removal Equipment Visibility Guide. This guide, which originated with a 2013 Ministry of Transportation of Ontario research project, includes recommendations for lighting and other conspicuity treatments. Other guidance related to winter maintenance equipment includes research and agency practices associated with lighting snowplows and other winter maintenance vehicles.

General Conspicuity

"Field Test of Visibility Markers for Snow Maintenance Equipment," Alison Smiley, Tom Smahel, Michael E. Pearsall and Tammy Dow, *TRB 96th Annual Meeting Compendium of Papers*, Paper #17-02142, 2017.
http://docs.trb.org/prp/17-02142.pdf
From the abstract:

> Due to the evolution of the use of private contractors in Ontario for highway snow removal a lack of consistency developed in the lighting and marking of maintenance vehicles. Due to safety concerns raised by operators of snow removal equipment, the Ministry of Transportation of Ontario (MTO) initiated the development of an updated standard for a lighting and marking system, to produce greater visibility/conspicuity of, and safety for, highway snow removal equipment and associated workers. The standard was developed through a multidisciplinary value engineering study. This

paper describes a series of tests that were carried out to assess the proposed lighting and marking system. Tests involved selection of highly conspicuous elements, determination of the conspicuity of brake lights, turn signals and rotators, in the presence of other system elements and assessment of driver ability to determine closing speed with the proposed system. The final standard included: A fluorescent yellow-green/black checkerboard with Type III/IV sheeting; Constant Amber + Flashing Blue LED [light-emitting diode] light bars to each side and above the checkerboard; Red and white retroreflective tape on an airfoil above the checkerboard; Upper and lower tail and brake lights; and Amber and blue rotating beacons, one on the roof of the cab and the other two near the top left and top right corners of the back of the snow removal equipment. This design has now been accepted and published as a national guideline by the Transportation Association of Canada.

Snow Removal Equipment Visibility Guide, Snowplow Lighting Joint Working Group, Transportation Association of Canada, 2015.
Citation at https://trid.trb.org/view/1399706
From the abstract:

Snowplows operate in some of the most adverse winter driving conditions clearing the roads of snow and ice for the safety of the motoring public. The efficient detection and recognition of the snowplow is critical for motorists in order to respond appropriately for the safety of all road users. The purpose of the Guide is to provide the information, analysis and testing available to road authorities and winter maintenance service providers. The information will assist road authorities and winter maintenance service providers to make their snow removal equipment as visible as possible and work towards increasing the consistency of the appearance of snowplows across Canada.

Related Resources:

"Re-Establishing a Brand: A New Ontario Standard for Snow Removal Equipment Visibility," *RoadTalk*, Ministry of Transportation of Ontario, Winter 2015.
http://aors.on.ca/wp-content/uploads/Road-Talk.pdf
In July 2013, MTO began a research project that resulted in a new lighting and visibility standard for snow removal vehicles and equipment. The project began with a review of previous research and literature, with a particular interest in lighting. A subsequent in-house study focused on the conspicuity panel, which is the large panel on the back of snow removal equipment that helps to identify it. In November 2013, the agency "conducted tests with nine different color and sheeting combinations during daytime and nighttime winter conditions. The tests demonstrated that the best conspicuity panel is a checkerboard pattern in fluorescent yellow-green and black."

"Snow Removal Equipment Visibility," Mike Pearsall, Head, Maintenance and Operations, Ministry of Transportation of Ontario, *AASHTO Value Engineering Peer Exchange*, August 2015.
http://sp.design.transportation.org/Documents/TC%20Value%20Engineering/2015%20VE%20Workshop/2015%20PPPs,Papers/VE%20Product%20Improvements;%20Snow%20Removal%20Equipment%20Visibility.pdf
This peer exchange presentation highlights the research that resulted in the updated equipment standards appearing in the recent TAC guidebook. Among the findings highlighted in this presentation:

Lighting Recommendations:

- Optimal light pattern of upper blue and amber beacons flash alternately at 1 Hz (rotating pattern).
- Amber and blue LEDs are positioned on the sides and top of the truck's rear box.
- Amber beacon stays on; blue beacon turns on and off.
- Light intensity adjustment (automatic dimmer) can be used for day and night settings.
- The combination of amber and green lights was found to conflict with other uses (volunteer firefighters and traffic signals), and also produced less visibility than the amber and blue combination.

Other Conspicuity Treatments:

- Airfoils are used to keep the LEDs clear.
- Testing confirmed that the conspicuity panel should be fluorescent yellow-green and black.
- Red and white tape should outline the rear box.

The final slide of the presentation (represented in Figure 2.1) provides the equipment standards established in 2014 as a result of MTO's research.

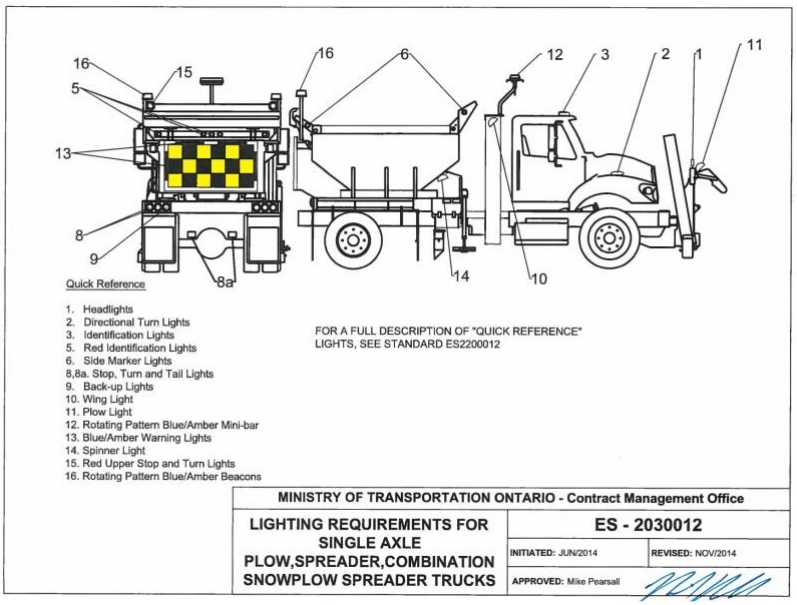

Figure 2.1 Ministry of Transportation of Ontario Lighting Requirements

Equipment Lighting: Related Research

Use of Equipment Lighting During Snowplow Operations: Final Report, Anburaj Muthumani, Laura Fay and Dave Bergner, Clear Roads Pooled Fund Study, October 2015.
http://clearroads.org/wp-content/uploads/dlm_uploads/FR_CR.14-06.pdf
This project used a literature search and agency and operator surveys to gather information about the current state of the practice and lessons learned with regard to the use of equipment lighting for snowplows and other winter maintenance equipment. Researchers used the information gathered to develop a series of best practices.

Highlights from Chapter 4, Conclusions and Recommendations, include the following (see page 8 of the report; page 17 of the PDF):

General Lighting:

- Use LEDs in new vehicles, retrofits and replacements due to improved visibility.
- Employ a mechanism to keep the lights clear of snow. (LEDs do not produce enough heat to melt snow and ice on the light surface.)
- Use wind deflectors and a heated lens to keep lights clear of snow.
- Mount auxiliary headlights away from the operator's line of sight (possibly at the lowest possible location on snowplow) to reduce light bounce-back.

Warning Lights:

- Amber is the color most commonly used for warning lights. However, agencies are using and/or testing blue, white and green colors.
- Use operator-preferred white warning lights because of perceived increased conspicuity during low-visibility conditions.
- Use both flashing lights and steadily burning lights that are spaced apart for rear warning lights.
- Use flashing lights to identify the presence of a plow and steady burning lights to aid in the estimation of the relative speed of the plow.

Retroreflectivity:

- Retroreflective tape markings are very effective and provide an additional level of warning for approaching vehicles.
- Keeping retroreflective markings clear of snow and visible at all times is an issue during snowplowing operations.
- Agencies can resolve the issue of increased brightness introduced by warning lights by using day-versus-night settings for lights on snowplow vehicles.

Related Resources:

Use of Equipment Lighting During Snowplow Operations: Synthesis of Information, Anburaj Muthumani, Laura Fay and Dave Bergner, Clear Roads, September 2015.
http://clearroads.org/wp-content/uploads/dlm_uploads/Synthesis_CR.14-06.pdf
This synthesis of information was used to develop the final report cited above.

"Use of Equipment Lighting During Snowplow Operations: Identified Best Practices," Laura Fay, *Pacific Northwest Snowfighters (PNS) Conference*, June 2016.
http://pnsassociation.org/wp-content/uploads/T9-1-Equipment-Lighting_PNS.pdf
This conference presentation provides highlights of the 2015 Clear Roads research project and includes photos and other graphics. Figures 2.2 and 2.3 provide a few examples.

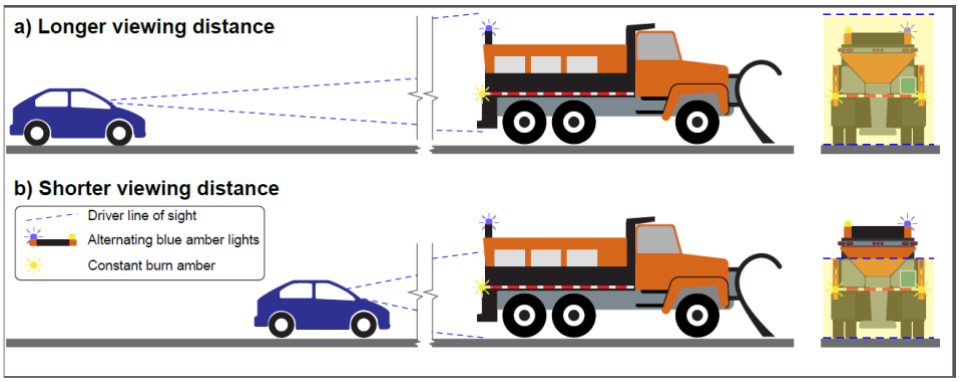

Figure 2.2 Proposed Mounting Location for Steady Burn and Flashing Snowplow Lights

Figure 2.3 Examples of Forward and Rear Snowplow Warning Lights

Snow Rendering for Interactive Snowplow Simulation—Supporting Safety in Snowplow Design, Peter Willemsen, Intelligent Transportation Systems Institute, Center for Transportation Studies, University of Minnesota, January 2013.
http://www.its.umn.edu/Publications/ResearchReports/pdfdownload.pl?id=2216
From the report's conclusions:

> In general, our experiments have found that increasing the information for optical expansion improves subject performance in the driving simulator. We believe that augmenting snowplow truck lighting arrays with information that frames the snowplow truck will improve safety. Additionally, it is likely that increasing, or maximizing the contrast of the LED light array on the truck will result in

drivers seeing the approach or withdrawal of a lead vehicle in a more timely manner. Any decrease in reaction time should help drivers detect the approach of a snowplow truck in a timelier manner and make winter driving safer.

Figure 4.1 on page 28 of the report (page 37 of the PDF), reproduced in Figure 2.4 below, shows the rear-end lighting recommended by researchers. The lighting application includes vertical bar lights that "are steady burning light arrays flanked by dense black bars to enhance and maximize contrast."

Figure 2.4 Snowplow Lighting Recommended by University of Minnesota Researchers

Researchers' experiments focused on how to improve reaction times in a driving simulator. Researchers noted that the lighting configuration used in Experiment 4 (as represented in Figure 2.4 above) does the following:

- Maximizes expansion information on the retina for impending collision.
- Improves drivers' detection of approach under low-contrast conditions.
- Allows drivers following snowplow trucks in the simulator to respond faster.

Winter Maintenance Improvements: Phase I, Cahit A. Evrensel, Yanyao Jiang, Kwang Kim, Onur Dur, Arthur Hu and Kurn Ma, Nevada Department of Transportation, April 2008.
https://www.nevadadot.com/home/showdocument?id=3812
Researchers evaluated a variety of technologies intended to improve visibility for the snowplow operator and visibility of the snowplow vehicle for motorists. The research team implemented and tested different types and configurations of warning lights to determine which combinations were the most visible to other motorists during snowplowing operations.

Researchers recommended a rear lighting system that "closely aligns with Idaho DOT winter maintenance vehicles." Such a system would include:

- LED brake/tail/turn lights that provide a high-intensity light in all directions.
- An LED light bar at both sides of the snowplow to provide "conspicuity and indication of width" of the plow.
- A light bar at the top of the sander "as a combination of LED, halogen or incandescent strobe."

- A relay system such as an "automatic delay system for rear flashing lights."

It was also recommended that "at least some of [the] LEDs of the aforementioned light bar [be] set to the steady burning mode and the rest should be on quad/comet flash mode. As indicated before, steady burning light bars improve drivers' ability to detect changes in [the] plow's speed and provide an indication of [the plow's] width."

Other findings:

- Flashing or strobing lights provide high conspicuity and signal drivers that the plow is operating.
- It is advisable to place the light sources farthest from the operator's line of sight.
- The plow's hood should be painted in a nonreflective color (i.e., black or brown) to prevent glare.
- Preference should be given to narrow-beam lamps (shielded headlamps, louvered or cut-off type) with sufficient heat discharge characteristics (incandescent, halogen) complemented by high-intensity discharge systems.

LED Lighting for Snow Plows and Related Maintenance and Construction Vehicles, Tim Vogt and Kenneth Miller, Minnesota Department of Transportation, August 2008.
http://www.lrrb.org/PDF/200829.pdf
From the abstract:

> The goal of this project was to understand the effectiveness of light emitting diode (LED) based lights for replacement of the standard strobes on Mn/DOT snow plows and to develop a set of specifications for LED based snow plow strobe lights. …The results suggest that LED based lights are comparable in conspicuity to the standard strobe lights currently used on Mn/DOT plows, under specific conditions. The authors found that when viewed from a direction corresponding to that typical of a vehicle approaching from the rear, the LED based lights were equally conspicuous as the standard strobe. However, when viewed from other angles the standard strobe outperforms the LED lights in field tests. A specification was not completed, but recommendations were made for possible improvements to LED based lights to improve field test results.

Equipment Lighting: Agency Practices

Idaho

"New Lights Curb Confusion and Car vs. Snowplow Accidents in Idaho," The Associated Press, *The Oregonian (Oregon Live)*, December 26, 2015.
http://www.oregonlive.com/pacific-northwest-news/index.ssf/2015/12/new_lights_curb_confusion_and.html
From the article:

> Idaho officials say changing the rear lights on snowplows from flashing yellow to flashing red has resulted in fewer mishaps by motorists approaching the road-clearing machines from behind.
>
> "Too many people were ignoring the flashing yellows and running right up to the snowplows," Idaho Transportation Department spokesman Reed Hollinshead told *The Lewiston Tribune.* "Flashing red definitely gets a driver's attention."

He didn't have exact numbers but said crashes have decreased since changing the lights three years ago.

Iowa

"Iowa DOT Testing Blue Lights to Increase Visibility of Snowplows," Blog Post, *Transportation Matters for Iowa*, Iowa Department of Transportation, November 2015.
http://www.transportationmatters.iowadot.gov/2015/11/iowa-dot-testing-blue-lights-to-increase-visibility-of-snowplows.html
From the blog post:

A new law passed in the last legislative session seeks to increase safety by allowing the Iowa DOT to add rear-facing white and blue lights in addition to the amber warning lights on vehicles as part of a pilot project. The lights will only be used during winter operations, a time in which snowplows are often moving much slower than the flow of traffic due to plowing and spreading material on the roadway. This slower speed is often one of the causes of crashes with snowplows.

Ken Morrow, from the Iowa DOT's Office of Maintenance, said, "For the pilot [project], we have equipped all the trucks in the central part of the state with the blue and white lights. We've also put blue and white lights on at least two trucks in each of the other five Iowa DOT districts. For many of the trucks that were not upgraded with blue and white lights, we've added additional amber lights to see if that impacts the visibility of the vehicles."
….

Morrow says the pilot project will last until 2018. At the end of the 2017-2018 winter season, crash data from all three years of the pilot project will be analyzed and a report will be presented to the legislature on the effectiveness of the lighting systems. Decisions on further implementation of the blue lights will be made following legislative and Iowa DOT review of the pilot.

Figure 2.5 shows placement of new blue lights and enhanced amber lights on some Iowa DOT snowplows.

Figure 2.5 New Rear Lighting on Some Iowa DOT Snowplows

Michigan

"When Green Means Slow: Winter Maintenance Vehicles Getting Green Lights to Improve Visibility," News Release, Michigan Department of Transportation, December 2016.
https://content.govdelivery.com/accounts/MIDOT/bulletins/177df30
From the news release:

> In an effort to reduce crashes, the Michigan Department of Transportation (MDOT) and several Michigan county road commissions and municipalities will be using green and amber lights that may be flashing, rotating or oscillating on 70 percent of their winter maintenance vehicles.
>
> "Our visual system would be more attracted to a bright green light versus a bright white flashing light in a heavy snowstorm," said Dr. Bernie Tekiele of the Michigan Eye Institute. "Our visual system is piqued to be sensitive to the green/yellow spectrum."
>
> Studies suggest that humans can differentiate more shades of green than any other color. Better visibility with green lights means safer roads for winter maintenance workers and motorists. The Kent County Road Commission (KCRC) has been piloting the green lights for the past two years with great success.

Related Resource:

> **Green Means Slow**, Michigan Department of Transportation, undated.
> http://www.michigan.gov/documents/mdot/WhenGreenMeansSlow_544477_7.pdf
> This one-page handout includes a depiction of a snowplow with the new green and amber lights that will be used on Michigan DOT and other Michigan snowplows. This publication indicates that the lighting changes are the result of a bill that amended the Michigan Vehicle Code.

"Superior Stick: Innovative Lighting System Makes Wing Plows More Visible," News and Information, Michigan Department of Transportation, February 2016.
http://www.michigan.gov/mdot/0,4616,7-151-9620-377797--,00.html
From the news release:

> The existing lighting systems available for wing plows had their own hydraulic systems to extend them from the body of the truck. While these systems worked well, they required added hydraulics and moving parts, which added expense and required more maintenance. A new, more foolproof wing plow lighting system, dubbed the "Superior Stick," was recently developed by Tom Deschaine and Jason Rankinen, state workers at MDOT's L'Anse Maintenance Facility.
>
> The stick attaches directly to the end of the plow and has no moving parts. It extends and retracts along with the wing plow blade to make the warning lighting highly visible and reliable. The lighting increases motorist safety and allows the deployment of the wing plow in a wider variety of situations. The system saw its first use last winter in MDOT's Superior Region, which encompasses the entire U.P. [Upper Peninsula].
> ….
> The first Superior Sticks were built by MDOT's L'Anse Garage staff partly with repurposed spare materials. Since then, a small machining and fabricating company, Johnson & Berry

Manufacturing in L'Anse, has produced some of the sticks, and MDOT will share the original concept with any other manufacturers interested in building them.

Figure 2.6 shows the Superior Stick installed on a wing plow used to clear active lanes of traffic and shoulders.

Figure 2.6 Michigan DOT's "Superior Stick"

Minnesota

Vehicle Warning Light Guidelines, Technical Memorandum No. 11-09-M-01, Engineering Services Division, Minnesota Department of Transportation, April 2011.
http://www.dot.state.mn.us/trafficeng/publ/pdf/11-09-M-01.pdf
These guidelines for the use of LED lights and blue lights indicate that the "goal is to have Mn/DOT's fleet of vehicles equipped with LED warning lights." Blue lights, mounted on the passenger side only, may be used on snow removal equipment and certain other vehicles. At the time of publication, no more than 50 percent of the light bar may be blue.

Missouri

LED Snow Plow Lights, Innovations Showcase, Missouri Department of Transportation, April 2015.
http://www.modot.org/innovationschallenge/documents/LEDSnowPlowLights.pdf
From the document:

Description
The LED Snow Plow Lights are a set of 1100 Lumen lights that put out a 60-degree cone of light to provide much better lighting when plowing roads and clearing intersections. LED lights on snow plow trucks greatly improve visibility while plowing snow.

Benefit
Improving visibility for snow plow operators has many benefits. With the LED lights in place, operators can plow snow more safely and reduce accidents. The lights make the job easier and more efficient with a clear view for clearing intersections and bridges. LED lights also reduce eye fatigue by reducing the strobe effect in the cab of the truck. Snow does not stick to these lights, eliminating the need for constant cleaning. LED lights would be useful in any night emergency operation, such as flood response and signing operations.

Ohio

"ODOT's New Colored Light Combinations on Snow Removal Equipment," Fact Sheet, Ohio Department of Transportation, undated.
http://www.dot.state.oh.us/Services/Pages/New-Colored-Light-Combinations-on-Snow-Removal-Equipment.aspx
This online fact sheet includes a video of Ohio DOT's new snowplow lighting and these highlights of the agency's new lighting directive:

- ODOT will use an amber, green and white color combination, all with different pulses.
- Studies suggest green lights are more easily detected by the human eye than other colors.
- These changes are a result of House Bill 487 (Mid-biennium Budget Review) ORC 4513.18. The law went into effect on September 10, 2012.
- The new law applies to headlights, clearance lights, identification lights and other lights on snow removal equipment.
- The new law permits the use of flashing colored lights other than blue or red (those colors are reserved for law enforcement and emergency vehicles).
- Ohio will be one of the first states to use multiple colored lights, and will be the first to use green.
- The agency's goal was to have one-third (approximately 500) of the fleet outfitted with the new lighting by the end of 2012, with each district having an equal number of trucks with new lights. The remainder of the fleet was scheduled to be retrofitted throughout 2013.
- The change to multicolored lights was driven by the number of vehicles rear-ending ODOT's plow trucks.

Figure 2.7 Ohio DOT's Combination of Colored Lights for Snowplows

Saskatchewan

"Blue and Amber Lights on Snow Plows," Ministry of Highways and Infrastructure, Government of Saskatchewan, undated.
http://www.highways.gov.sk.ca/adx/aspx/adxGetMedia.aspx?DocID=759,104,81,1,Documents&MediaID=9638&Filename=Fact+Sheet+-Blue+and+Amber+Light+Sequence.pdf
This fact sheet/Q&A describes the use of blue and amber lights on all provincial snow removal equipment during regular winter maintenance activities. The new lighting was activated in December 2015. *From the fact sheet*:

- Provincial legislation now allows flashing blue lights—in combination with the current amber lights—to distinguish snow removal equipment (plows, graders, snowblowers, trucks) from other equipment that uses amber lights, such as tow trucks or oversized-load trucks. Use of blue lights for any other purpose is prohibited.
- The lights are activated when the equipment is conducting winter maintenance activities—plowing, sanding, salting or doing surveillance work on the highways. Winter maintenance involves monitoring the highways for snowdrifts or icy sections when operators may be required to put down the blade to remove a drift or spread some sand or salt at a moment's notice.
- Motorists on the highways are required to slow to 60 km/h when passing a plow (from either direction) with its blue and amber lights flashing. The same law applied prior to the introduction of the blue lights legislation.

Related Resource:

> **"Blue Flashing Lights to Be Added to Saskatchewan Snowplows,"** *CBC News*, CBC/Radio-Canada, November 5, 2015.
> http://www.cbc.ca/news/canada/saskatchewan/blue-lights-being-added-to-snowplows-1.3305588
> *From the article*:
>
> > To avoid confusion, the province plans to put blue lights on all its snow-clearing graders and plows, starting in January. That means when the plows are just driving, the amber "over-width" lights will be on. When the truck is actively plowing, the blue lights will be used.

2.2 Other Vehicles and Equipment

National Guidance

Proposed Project: Guidelines for Vehicle and Equipment Color, Marking and Lighting, NCHRP Project 05-24, close date for request for proposals: December 21, 2017. (Phase I of the project is expected to require six months; Phase II will require 24 months.)
Project description at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4359
From the objective:

> The objective of this research is to develop guidelines, for consideration and adoption by AASHTO, for the selection and application of color, retroreflective markings and lighting to vehicle[s] and equipment that will effectively identify vehicles and equipment, and communicate their activities to the motoring public, and thus enhance safety. This research is concerned with transportation-

agency roadway-operations vehicles and equipment used for construction, maintenance, incident response and other similar activities.

NCHRP Report 624: Selection and Application of Warning Lights on Roadway Operations Equipment, Ronald B. Gibbons, Suzanne E. Lee, Brian Williams and C. Cameron Miller, 2008.
Report available at http://www.trb.org/Publications/Blurbs/160388.aspx
From the foreword:

> This report presents recommended guidelines for the selection and application of warning lights on roadway operations equipment. The recommended guidelines address the physical, functional, and performance requirements of the lighting system, recognize that the lighting system on these vehicles must be designed and laid out with consideration to the planned or expected vehicle usage, and provide technical information for use in developing procurement specifications for specific applications. The content of the report will be of immediate interest to maintenance professionals and others involved in specifying warning lights on roadway operations equipment.

State Research and Practices

Indiana

Investigation of the Effective Use of Warning Lights on Indiana Department of Transportation (INDOT) Vehicles and Equipment, Bob McCullouch and Brandon Stevens, Indiana Department of Transportation, December 2008.
http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2650&context=jtrp
This report describes an effort to identify more effective lighting for Indiana DOT vehicles. The study examined five categories of lighting:

- Round and oval.
- LED surface.
- Light bars.
- Beacons.
- White lights.

Researchers conducted field observations using direct light observation in various types of conditions, weather and lighting. Among the study's conclusions:

- LED lights were observed as brighter than others and produced similar results across all observation conditions. In comparisons between the different light groups (round, surface, etc.), LED lights were preferred.
- Amber is the clear color preference across all color configurations. Amber was perceived by the observers as the brightest across all observation conditions. The second choice of color is bright blue, a color similar to that used by law enforcement vehicles. Researchers noted that use of blue lights may be restricted by state law.
- Larger lights were observed to be more visible than smaller lights.

Kentucky

Work Vehicle Warning Lights: Color Options and Effectiveness, Brian Howell, Jerry Pigman and Ken Agent, Kentucky Transportation Cabinet, September 2015.
https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=2504&context=ktc_researchreports
From the abstract:

> KTC [Kentucky Transportation Center] conducted two external surveys to assess warning light products and practices within the U.S. The first survey reviewed vendor LED products and revealed that LED lights are primarily available in the colors of amber, blue, green, red and white. Fluorescent yellow-green is not available. The second survey requested state DOT information related to lighting systems' colors, sources, intensity, and placement; responding agency names and policies; and previous state DOT studies related to warning lights.

The state survey was conducted in June 2015 and generated 16 responses. Survey findings include the following:

- 100 percent of survey respondents use the color amber and LED light sources.
- More than 75 percent of reporting agencies place warning lights on a highway work vehicle's roof to maximize visibility to motorists.
- Survey results varied dramatically on the differentiation of warning light colors by vehicle type and on the differentiation of light intensities for daytime versus nighttime conditions.

Researchers noted that other state agencies have conducted studies to identify optimal colors for vehicle warning lights. These agencies and their conclusions include the following (from page 15 of the report, page 24 of the PDF):

- Illinois State Police: The colors of white, amber, red and blue could be seen from the greatest distances (in order of greatest to least visibility).
- Indiana DOT: Amber is the strongest color for visual acuity.
- Iowa DOT: Amber is the primary state DOT color of choice for vehicle warning lights.
- Minnesota DOT: Amber and blue lights are used on the agency's supervisory maintenance vehicles.
- Ohio DOT: Green warning lights are used for select highway vehicles.
- Texas DOT: Amber is the most commonly used color for highway vehicle warning lights (as determined by a survey conducted by the Texas Transportation Institute).

From the researchers' recommendations (Section 5.2 of the report, appearing on page 16 of the report, *page 25 of the PDF):*

> The Kentucky Transportation Center recommends the following measures for use in the Kentucky Transportation Cabinet's [KYTC's] highway work vehicle warning light program:
>
> 1. Use amber and white colors for all KYTC work vehicle warning lights.
> 2. Use asynchronous flashing pattern (flashing from side to side) consisting of slow flash frequencies (≈ 1 Hz) for vehicle warning lights.

3. Use LED lights with a minimum intensity of 4,000 and 1,650 lumens for daytime and nighttime conditions, respectively.
4. Place warning lights on highway work vehicles, preferably at higher elevations on the vehicle, so they can be seen at any angle of approach.
5. Place warning lights on highway work vehicles against solid-colored backgrounds to provide contrast.
6. Consult with approved LED vendors to investigate the feasibility of the yellow-green color in warning lights.

Mid-America Transportation Center

Improving Work Zone Safety for Freight Vehicles: Effective Design Patterns for Vehicle Mounted Attenuators, Ghulam H. Bham, Ming C. Leu, Durga Raj Mathur and Manoj Vallati, Mid-America Transportation Center, December 2010.
http://matc.unl.edu/assets/documents/matcfinal/Bham_ImprovingWorkZoneSafetyforFreightVehiclesEffectiveDesignPatternsforVehicleMountedAttenuators.pdf
From the abstract:

> This report presents a study of driver perceptions using a driving simulator carried out on the effectiveness of four markings which vary in striping patterns and color combinations used at the rear of vehicle mounted attenuators (VMAs) in work zones during daytime, dusk and nighttime.

Researchers considered the effectiveness of four different striping patterns:

- Lime green and black inverted “V” pattern.
- Red and white checkerboard pattern.
- Yellow and black inverted “V” pattern.
- Orange and white vertical stripes pattern.

Study results led researchers to recommend the use of a red and white checkerboard marking (see Figure 2.8).

Figure 2.8 Recommended Checkerboard Marking Pattern (Mid-America Transportation Center)

Researchers did note, however, that motorists "are not accustomed to the red and white color combination in the work zones. With regular use of the red and white checkerboard marking, it is expected to increase the rate of alerting drivers to work zones."

Other recommendations:

- VMA markings that are retroreflective should be field-tested at night.
- Further investigation of study findings by other states is advised before recommendations are made to update the guidelines for VMA markings.
- VMA patterns should be evaluated for different heights.
- The visibility of VMAs should be studied for different flashing patterns of strobes, rotating beacons, retroreflective tape and different intensities of strobe lights to improve the visibility of VMAs during the night and for different work zone configurations.
- VMA patterns should be evaluated for color-deficient drivers.

Missouri

Fleet Lighting Levels and Conspicuity Tape, Missouri Department of Transportation, undated.
http://epg.modot.org/files/4/49/616.27_Fleet_Lighting_Guidelines.pdf
This document provides a description, examples and images for each level of fleet lighting and use of conspicuity tape. General recommendations include the following:

- Beacons or mini-light bars should be installed at the highest point possible and should not be blocked by equipment such as v-beds and luggage racks.
- The use of a dimmer function should be considered during nighttime operations for higher-intensity lighting such as longer light bars and bright white LEDs.
- The switch for fleet lighting should be easily accessible and visible to the operator. If possible, the switch should have an indicator light to prevent the switch from being inadvertently left on.
- The indicator light should not be installed in a way that could cause a reflective glare inside the equipment or vehicle that could interfere with its operation.
- If possible, the switch should not use a factory power supply or cigarette lighter.

The document also includes the May 2013 Guidelines on Warning Lights for MoDOT fleet (see page 15 of the PDF).

Related Research

"Evaluation of Light-Emitting Diode Warning Beacons for Maintenance Vehicles," John D. Bullough and Nicholas P. Skinner, *TRB 90th Annual Meeting Compendium of Papers*, Paper #11-0490, 2011.
http://docs.trb.org/prp/11-0490.pdf
Researchers' results, as described in this conference paper's abstract, include the following:

- Pairs of LED warning beacons provided equivalent closure detection distances to a pair of conventional rotating beacons.

- While single LED warning light configurations were not tested, the pairs of LED beacons tested reliably outperformed a single conventional beacon configuration in terms of both energy use and closure detection distance.
- Overall, the results suggest that LED warning beacons provide comparable visual information to other drivers, while using substantially less power than conventional rotating beacons.

3 Other Vehicle Types

To supplement the examination of research and practices associated with DOT equipment conspicuity, we sought information about the conspicuity of other vehicle types, including vehicles used at airports and those used for emergency purposes and by law enforcement.

3.1 Airport Vehicles

"Painting, Marking, and Lighting of Vehicles Used on an Airport," Advisory Circular, Federal Aviation Administration, April 2010.
https://www.faa.gov/documentlibrary/media/advisory_circular/150_5210_5d.doc
From the document:

> **PURPOSE.** This advisory circular (AC) provides guidance, specifications, and standards for painting, marking, and lighting of vehicles operating in the airport air operations area (AOA). The approved lights, colors, and markings herein assure the conspicuity of vehicles operating in the AOA from both the ground and the air.

Other excerpts:

> **NOTE:** A yellowish-green color provides optimum visibility during all light levels encountered during a 24-hour day and under variations of light that result from weather and seasonal changes.
>
> **(5)** To further improve night-time recognition of vehicles, a minimum 8 inch (200 mm) wide horizontal band of high gloss white paint or white reflective tape (Retroreflective, ASTM-D 4956-09, *Standard Specification for Retroreflective Sheeting for Traffic Control*, Type III & above) must be used around the vehicle's surface.

3.2 Emergency and Law Enforcement Vehicles

Domestic Resources

Lights and Siren Use by Emergency Medical Services (EMS): Above All Do No Harm, Douglas F. Kupas, National Highway Traffic Safety Administration, May 2017.
https://www.ems.gov/pdf/Lights_and_Sirens_Use_by_EMS_May_2017.pdf
From the introduction:

> The purpose of this report is to review the use of L&S [emergency warning lights and siren] during EMS vehicle operations, including the impact of L&S use on effectiveness in saving time, safety, public perception, and medical outcomes.

See page 21 of the report for a discussion of the use and usefulness of emergency warning lights and vehicle conspicuity. EMS agencies are encouraged to consider:

- Using a lime-green vehicle color, which has the maximum conspicuity. Alternatively, consider avoiding black, dark blue or dark red for the EMS vehicle's color, which are least visible.
- Avoiding patterns, pictures and emblems that may be camouflaging.
- Using retroreflective material to outline the vehicle in darkness.
- Applying a fluorescent, outward-downward chevron pattern of retroflective sheeting on the back of the vehicle.

Emergency Vehicle Safety Initiative, U.S. Fire Administration, Federal Emergency Management Agency, February 2014.
https://www.usfa.fema.gov/downloads/pdf/publications/fa_336.pdf
This report highlights research studies that suggest "a number of practical things that law enforcement agencies, EMS providers and fire departments can do to enhance the ability of drivers to see and recognize emergency vehicles during all phases of an incident." Below are excerpts that begin on page 71 of the report:

Contour Markings
Outlining vehicle boundaries with "contour" or "edge" markings using retroreflective material should help enhance emergency vehicle visibility/conspicuity. The potential value of outlining a vehicle is supported by research going back to 1984 (Henderson et al., 1984). In an extensive study of various marking schemes for large trucks, Darmstadt University of Technology researchers found contour markings useful for improving both side and rear visibility (Schmidt-Clausen, 2000).

Placement
Newer versions of vehicle headlamps used in passenger and commercial vehicles change the way the road ahead is illuminated, including traffic signs, people and emergency vehicles. Studies (Chrysler et al., 2002; Sivak et al., 2006) of recent changes in headlamp illumination suggest that it might be effective to concentrate retroreflective material lower on emergency vehicles to optimize interaction with approaching vehicles' headlamps. This opportunity complements the anticipated positive effects of contour markings outlining an emergency vehicle's overall size and shape.

Fluorescent Colors
Fluorescent retroreflective materials, especially yellow and orange, have superior conspicuity properties and are particularly useful where a high degree of daytime visibility is desired (Zwahlen and Vel, 1994). The increasing use of fluorescent colors will likely prove beneficial for providing 24/7/365 high conspicuity on fire apparatus and ambulances. Mission requirements for law enforcement vehicles should drive decisions about whether to incorporate fluorescent colors. For example, a traffic enforcement vehicle designed to be inconspicuous will probably not use fluorescent colors to enhance its daytime visibility.

Efficiency
Using high-efficiency retroreflective material can improve conspicuity while reducing the amount of vehicle surface area requiring treatment. Some studies of retroreflective sheeting types in traffic control applications suggest that the cost increase to specify higher-efficiency retroreflective material can be reasonably expected to pay off by reducing crashes under some scenarios (Gates and Hawkins, 2004; Amjadi, 2008). However, as noted by Chrysler and others (2002), all visual performance factors must be considered; performance should be evaluated for all lighting and weather conditions; and durability, ease of fabrication and cost must be weighed against the benefits of each product.

Emergency Vehicle Visibility and Conspicuity Study, Federal Emergency Management Agency, August 2009.
https://www.usfa.fema.gov/downloads/pdf/publications/fa_323.pdf
This report "analyzes emergency vehicle visibility and conspicuity with an eye toward expanding efforts in these areas to improve vehicle and roadway operations safety for all emergency responders. Emphasis in this report is placed on passive visibility/conspicuity treatments." Below are excerpts that begin on page 22 of the report:

> **Contrast**
> The use of contrasting colors can positively affect conspicuity by assisting drivers with locating a hazard amid the visual clutter of the roadway. There are basically two types of contrast: 1) luminance contrast—the degree to which an object is brighter than its background, and 2) color contrast—the difference in an object's color(s) and those found in its background. (Cook et al., 1999) Contrast is enhanced by using colors not normally found in the environment, including fluorescents.
>
> **Fluorescent Colors**
> The effectiveness of fluorescent colors for enhancing daytime visibility/conspicuity in traffic safety applications is well-established in the literature. (Smith, 1981; Zwahlen & Vel, 1994; Cook et al., 1999; Anders, 2000; Hawkins et al., 2000; Krull & Hummer, 2000; Schieber et al., 2003; Buonarosa & Sayer, 2007) Since fluorescence relies on ultraviolet radiation, fluorescent colors offer no additional benefit at night:
>
> > *Fluorescent colors are brighter than ordinary colors because they are capable of converting light energy that is normally absorbed and wasted to visible light, which in turn reinforces the color in intensity. Hence, there is greater visibility in daylight conditions. (Smith, 1981)*
>
> The specific color choice may or may not be important with respect to fluorescents, perhaps depending on background characteristics. In a 1994 study, "...fluorescent yellow was found to be best detected and fluorescent orange was found to be best recognized against any of the three backgrounds investigated." (Zwahlen & Vel, abstract) A recent study of traffic safety garments showed no statistical difference in the daytime conspicuity of fluorescent red-orange and fluorescent yellow-green, although fluorescent yellow-green had a significantly higher luminance value, compared to the background, than the fluorescent red-orange. (Buonarosa & Sayer, 2007) Research performed at the Texas Transportation Institute also demonstrated the benefits of fluorescent colors, in this case fluorescent-orange work zone signs, citing greater recognition distance and accurate color perception during the day. (Hawkins et al., 2000)

International Resources

"Determining Optimum Flash Patterns for Emergency Service Vehicles: An Experimental Investigation Using High Definition Film," Sally Turner, Julie Wylde, Martin Langham and Andrew Morrow, *Applied Ergonomics*, Vol. 45, No. 5, pages 1313-1319, September 2014.
Citation at http://www.sciencedirect.com/science/article/pii/S0003687013001178
From the abstract:

> An investigation of how emergency vehicle lighting (EVL) can be improved is reported with reference to an analysis of police vehicle road traffic accidents (Study 1). In Study 2, 37 regular drivers were shown film clips of a marked police vehicle, in which flash rate (1 Hz, 4 Hz) and pattern (single, triple pulse) were varied on the blue Light Emitting Diode (LED) roofbar. Results indicate a 4 Hz flash rate

conveys greater urgency than a 1 Hz rate, while a 1 Hz, single flash combination was ranked the least urgent of all combinations. Participants claimed they would leave significantly more space before pulling out in front of an approaching police car (gap acceptance) in the 4 Hz single pulse condition in comparison to other EVL combinations. The preliminary implications for which flash characteristics could prove most optimal for emergency service use are discussed with regard to effects on driver perception and expected driving behaviour.

4 General Vehicle Conspicuity

The publications below examine vehicle lighting, vehicle color and retroreflective markings used to enhance the conspicuity of vehicles employed for purposes other than DOT maintenance.

4.1 Vehicle Lighting

Domestic Resources

Adaptive Driving Beam Headlights: Visibility, Glare and Measurement Considerations, J. D. Bullough, N. P. Skinner and T. T. Plummer, Transportation Lighting Alliance, June 2016.
http://www.lrc.rpi.edu/programs/transportation/TLA/pdf/TLA-2016-01.pdf
This research examines the efficacy of adaptive driving beam (ADB) headlight systems, which "can detect both oncoming headlights and preceding taillights and reduce their intensity only in the direction of the other lights while maintaining higher levels of illumination throughout the remainder of the field of view." Findings from this project's experiments "suggest that ADB systems can offer safety benefits compared to conventional headlight systems." However, at the time of publication, ADB systems are not defined in North American headlighting standards. Researchers provide recommendations for standardized measurement conditions to ensure reliability.

Effects of Warning Lamp Color and Intensity on Driver Vision*,* Michael J. Flannagan, Daniel F. Blower and Joel M. Devonshire, U.S. Department of Homeland Security, Federal Emergency Management Agency, U.S. Fire Administration, and U.S. Department of Justice, October 2008.
http://www.sae.org/standardsdev/tsb/cooperative/warninglamp0810.pdf
From the executive summary:

> Based on the results of the experiment, and on previous results in the literature, we offer three major recommendations for the use of warning lamps:
>
> 1. Use different intensity levels for day and night;
> 2. Make more use of blue overall, day and night; and
> 3. Use color coding to indicate whether or not vehicles are blocking the path of traffic.
>
> In future research, we recommend that the following issues be addressed:
>
> 1. Better definition of and measures for "effective" intensity of flashing lamps;
> 2. The relationship between subjective conspicuity and objective search performance;
> 3. Further development and validation of search tasks for evaluating warning lamps; and
> 4. More comprehensive data on color effects in daytime and nighttime.

International Resources

"All Things Bright and Debatable," Howard Redwood, *Driving Magazine*, No. 22-3, January/February 2011.
http://www.lightmare.org/docs/DIA%20All%20things%20bright%20and%20debatable%20Jan%202011.pdf
This magazine article describes three types of "eye disability" that result from glare:

- Veiling disability occurs when a light source reduces the contrast of a visual target by superimposing light on the visual target's retinal image. An example would be to look at a person standing in front of a sun-filled window.
- Dazzle disability occurs when a bright light concentrates towards the viewer's central field of vision, changing the contrast between the lighter and darker details. An example is when oncoming headlights fill more space than they should, making it difficult for the viewer to make distinction between darkness and light.
- Scotomatic disability occurs when a brilliant light source decreases visual sensitivity, or "puts a retinal area out of business." An example is an extremely strong light quite often in the blue wavelength, like a flash from a camera causing rapid bleaching of the retinal eye receptors.

The article then addresses how the improper use of Xenon lights and LEDs in passenger vehicles can cause these "disabilities" to occur:

> Due to the nature of the intensity of Xenon lights and, to some extent, Light Emitting Diodes (LEDs), incorrect horizontal and vertical positioning can cause all three of the above disabilities to take place. The Xenon system relies on a floating system that responds to sensors on the vehicle's suspension. The problem with this is that the horizontal plane responds in a reactive measure—slightly after the wheels have left the dip in the road. This late response brings the lights up when the vehicle is on a higher plane causing one of the three dazzling effects. The Xenon system has no scroll switch for manual adjustment, and thus relies on the manufacturer's factory setting. The retrofits are a problem, [and] unless the consumer has technological software to read the vehicle on-board computer data, the lights will almost certainly be incorrectly set.

4.2 Vehicle Color

Domestic Resources

Effect of Vehicle Color and Background Visibility for Improving Safety on Rural Kansas Highways, Sunanda Dissanayake, Thomas Hallaq, Hojr Momeni and Nick Homburg, Kansas Department of Transportation, June 2015.
https://rosap.ntl.bts.gov/view/dot/28921
From the abstract:

> In this research, a stopped vehicle was simulated at a rural intersection in Kansas, where a large number of crashes have occurred. Various vehicles with different colors approaching from eastbound and westbound directions under different daytime light conditions were shown to participants. Response times of participants to identify the approaching vehicles were measured for each vehicle color under different conditions.
> ….

> Considering the aforementioned results of data analysis, findings of this research do not conclude that the differences between the response times to colors are consistent, meaning a specific color does not stand out above the others. Despite differing lighting conditions where some colors were slightly more recognizable, the difference is not uniformly significant. Based on the results of this study, there is not enough evidence to determine that the elevated number of crashes at the study intersection is due to camouflaging of vehicles due to coloring, and no other immediate cause can be identified.

International Resources

"Yellow Taxis Have Fewer Accidents Than Blue Taxis Because Yellow Is More Visible Than Blue," Teck-Hua Ho, Juin Kuan Chong and Xiaoyu Xia, *Proceedings of the National Academy of Sciences*, Vol. 114, No. 12, pages 3074-3078, March 2017.
Citation at http://dx.doi.org/10.1073/pnas.1612551114
From the abstract:

> Is there a link between the color of a taxi and how many accidents it has? An analysis of 36 mo[nths] of detailed taxi, driver, and accident data (comprising millions of data points) from the largest taxi company in Singapore suggests that there is an explicit link. Yellow taxis had 6.1 fewer accidents per 1,000 taxis per month than blue taxis, a 9% reduction in accident probability. [The authors] rule out driver difference as an explanatory variable and empirically show that because yellow taxis are more noticeable than blue taxis—especially when in front of another vehicle, and in street lighting—other drivers can better avoid hitting them, directly reducing the accident rate. This finding can play a significant role when choosing colors for public transportation and may save lives as well as millions of dollars.

4.3 Retroreflective Markings

Domestic Resources

"Light Reflections," Kevin Brinker (Avery Dennison USA), *Intertraffic World*, Issue 1 (launch issue), pages 44-46, 2010.
http://viewer.zmags.com/publication/58440222 (Go to page 44 of this online magazine.)
This journal article describes the next generation of reflective materials—full cube prisms, which eliminate dead spots on the edges of the prism. As the article indicates, "With full cube prism sheeting, better management of the reflected light may be possible in order to meet the observation and entrance angles of specific driver/vehicle types."

"Quantifying the Subjective Brightness of Retroreflective Material Using Magnitude Estimations," Justin S. Graving, Richard A. Tyrrell and Stacy A. Balk, *Proceedings of the 5th International Driving Symposium on Human Factors in Driver Assessment and Vehicle Design*, 2009.
http://drivingassessment.uiowa.edu/DA2009/052_GravingTyrrell.pdf
From the introduction:

> Considering that previous research on the relationship between brightness and luminance has shown that increasing luminance increases brightness (Stevens, 1957), in the current experiment it was expected that brightness, measured using magnitude estimations, would show such a

relationship with increases in retroreflection. In the current study brightness will be compared to retroreflection whereas typically brightness is compared to luminance.

The conference paper's summary describes the research approach and results:

> Ten small patches of retroreflective material were evaluated using a method of magnitude estimation to quantify the effect of changing the coefficient of retroreflection (R_A) on brightness perception. Seventeen undergraduates participated. The results show that brightness is tightly linked withR_A. Brightness was influenced more by changes in lower R_A than changes in higher R_A and follows Stevens's power law for brightness.

International Resources

"Effectiveness of Retroreflective Tape at Rear End of Heavy Trucks to Increase Visibility and Reduce Rear-End Collisions," Trinh Thi Lan, Kunnawee Kanitpong, Kazuya Tomiyama, Akira Kawamura and Takashi Nakatsuji, *TRB 96th Annual Meeting Compendium of Papers*, Paper # 17-03792, 2017.
Citation at https://trid.trb.org/view/1438506
From the abstract:

> The purpose of this study is to compare the visibility of various colors and patterns of retroreflective tapes and to evaluate the effect of human factors and environment factors on detection distance, perception-reaction time, and heart rate when driving following heavy trucks with different patterns of retroreflective tapes. …The results of the study clearly show that the red and yellow combination of retroreflective tape placed horizontally and vertically on both right and left and upper and lower rear section of trucks following Regulation No. 48 from UNECE is the most visible retroreflective tape pattern comparing to others. Gender, driver age, driving speed of following vehicle, tape width, tape patterns, lighting condition, and weather condition significantly affect the detection distance. Driver age significantly affects the perception-reaction time. When driving following truck[s] with no retroreflective tape at rear end, the perception-reaction time is significantly longer. Therefore, the selection of the most effective color and pattern of retroreflective tape is very important in order to increase the visibility of heavy trucks and reduce chance of rear-end truck collision, particularly at nighttime or in limited visibility condition.

"Improving Road Safety Through Truck Visibility," Pippa Batchelor, *Journal of the Australasian College of Road Safety*, Vol. 25, No. 3, pages 54-56, September 2014.
http://acrs.org.au/wp-content/uploads/ACRSjournalVol25No3Aug14WEB.pdf (See page 54 for the article.)
From the article:

> Currently, ADR13/00 refers to the UNECE [United Nations Economic Commission for Europe]104 regulation for best practise vehicle marking. In order to be compliant with UNECE104, reflective tapes must be independently tested for photometric and physical performance. They are then awarded a unique identifier number which is printed (repeating) along the length of each tape. The regulation allows red, white and yellow tapes. Fluorescent yellow also fits into the yellow colour requirements and gives additional daytime visibility benefits. The Australian Trucking Association has produced a free Technical Advisory Procedure booklet which outlines these best practices for trucks. As a basic guide, the markings should cover at least 80% of the overall length of the vehicles and indicate its full outline. As a minimum, partial markings should be applied.

Related Resources:

Regulation No. 104, Uniform Provisions Concerning the Approval of Retro-Reflective Markings for Vehicles of Category M, N and O, United Nations Economic Commission for Europe, March 2010.
https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r104rev.1.e.pdf
This regulation is referenced in the article above and the citations that follow. The regulation applies to retroreflective markings for the following vehicle categories:

- Category M2: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tons.
- Category M3: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tons.
- Category N: Motor vehicles with at least four wheels designed and constructed for the carriage of goods.
- Category O2: Trailers with a maximum mass exceeding 0.75 tons but not exceeding 3.5 tons.
- Category O3: Trailers with a maximum mass exceeding 3.5 tons but not exceeding 10 tons.
- Category O4: Trailers with a maximum mass exceeding 10 tons.

"Vehicle Conspicuity Markings—REMA Guide for Purchasers," Retroreflective Equipment Manufacturers Association (REMA), undated.
https://cdn.shopify.com/s/files/1/0249/1325/files/REMA_vehicle-conspicuity-bulletin.pdf
From the guide:

> In July 2011 legislation made marking to ECE104 mandatory on new trucks and trailers, and the new DfT [Department for Transport] Code of Practice for Safety at Street Works and Road Works will require rear conspicuity markings on *all* works vehicles, whether new or not. However, vehicle operators are strongly advised to adopt compliant marking for their vehicles now as Highways Agency contracts already require it. DfT Guidance on marking is published in Chapter 8 of the Traffic Signs Manual and failure to follow safety guidelines and best practice carries the risk of substantial legal liability or even criminal charges should this result in a serious accident. ….
>
> REMA has been established over 30 years as the UK's [United Kingdom's] only trade association for manufacturers of retro-reflective traffic safety products and has therefore prepared this guide to help users cut through the "red tape" and specify appropriate (and legal) markings for their fleets.

"Keeping People Safer Through Better Visibility: Advances in Retroreflective Technologies for Road Signage, Pavement Markings and Vehicle Visibility Delivering Safer Roads," Agota Berces and Storm Robertson, *Australasian Road Safety Research, Policing and Education Conference*, October 2012.
http://acrs.org.au/files/arsrpe/Berces%20and%20Robertson%20-%20Keeping%20people%20safer%20through%20better%20visibility.pdf
As this conference presentation notes, "The risk of an accident between a truck and a car is 30 times greater when a truck does not have high-visibility vehicle markings. (Morgan) This chilling fact is a key

reason why the European Union have made high-visibility truck markings compulsory in Europe under UN/ECE 104, effective from October 2011."
From the abstract:

> This presentation looks to communicate a basic understanding of the science behind retroreflective materials as well as the new technologies that are available in the market. It looks at how these materials affect different road users including older drivers as well as those in larger vehicles such as trucks. It includes current global perspective on the use of these materials including research, international standards and best practice from other countries as well as Australasian solutions for road safety creating better and safer places to travel and live.

"Advances in Retroreflective Technologies for Road Signage, Vehicle Visibility and Pavement Markings, Delivering Safer Roads for All," A. King (3M Traffic Safety Systems Division), *5th Australian Road Engineering and Maintenance Conference*, 2010.
http://acrs.org.au/files/papers/13%20King%20Advances%20in%20retroflective%20technologies.pdf
From page 7 of the conference paper:

> To further improve vehicle visibility, especially in the areas of heavy vehicles and road working vehicles, it should be considered to adopt new vehicle marking guidelines and increase standards to improve safety. For heavy vehicles this may be based on the UN/ECE 104 and look to include upgrading of all vehicles to have high performance retroreflective markings on their sides. For Road Work vehicles which includes Construction Work Zone vehicles, as well as vehicles that may be doing work on or near a road eg: Electricity, water, road services etc, the use of the retroreflective materials would improve their overall visibility and increase their workplace safety.

5 High-Visibility Garments

The publications below review the use of luminescent panels or other high-visibility materials in garments to improve pedestrian and worker safety.

"Electroluminescent Materials Can Further Enhance the Nighttime Conspicuity of Pedestrians Wearing Retroreflective Materials," Drea K. Fekety, Darlene E. Edewaard, Ashley A. Stafford Sewall and Richard A. Tyrrell, *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 58, No. 7, pages 976-985, November 2016.
Citation at http://dx.doi.org/10.1177/0018720816651535
From the abstract:

> **Objective:**
> We investigated the nighttime conspicuity benefits of adding electroluminescent (EL) panels to pedestrian clothing that contains retroreflective elements.
>
> **Background:**
> Researchers have repeatedly documented that pedestrians are too often not sufficiently conspicuous to drivers at night and that retroreflective materials can enhance the conspicuity of pedestrians. However, because retroreflective elements in clothing are effective only when they are illuminated by the headlamps of an approaching driver, they are not useful for pedestrians who are positioned outside the beam pattern of an approaching vehicle's headlamps. Electroluminescent materials—flexible luminous panels that can be attached to clothing—have the potential to be well suited for these conditions.

Method:
Using an open-road course at night, we compared the distances at which observers responded to pedestrians who were positioned at one of three lateral positions (relative to the vehicle's path) wearing one of two high-visibility garments.

Results:
The garment that included both EL and retroreflective materials yielded longer response distances than the retroreflective-only garment. This effect was particularly strong when the test pedestrian was positioned farthest outside of the area illuminated by headlamps.

Conclusion:
These findings suggest that EL materials can further enhance the conspicuity of pedestrians who are wearing retroreflective materials.

High Visibility Apparel in Work Zones: Characteristics of High-Visibility Safety Apparel, American Traffic Safety Services Association, 2009.
https://www.workzonesafety.org/files/documents/training/fhwa_wz_grant/atssa_high_visibility_pocket_guide.pdf
From the introduction to this pocket guide:

> This guide outlines different apparel and the appropriate situations where each type of apparel is required or recommended by National standards/guidelines. When selecting the appropriate apparel, you should also check State and local requirements.

Seasonal Variations in Conspicuity of High-Visibility Garments, Mary Lynn Buonarosa and James R. Sayer, The University of Michigan, Industry Affiliation Program for Human Factors in Transportation Safety, November 2007.
https://deepblue.lib.umich.edu/bitstream/handle/2027.42/58731/100249.pdf?sequence=1
From the abstract:

> A naturalistic, daytime field study was conducted to investigate the effects of garment color, the amount of background material, driver age, and season on the conspicuity of high-visibility safety garments. Subjects drove an instrumented vehicle along a 29-km route once in the summer and again in the fall. Their task was to detect pedestrians wearing high-visibility garments. Distances at which pedestrians were first detected were recorded. All of the challenges normally encountered when driving on public roadways were present, thus providing a more ecologically valid level of workload than provided by test-track or static evaluations.
>
> The results show that the amount of background material and season significantly affected the detection distance of a pedestrian wearing a fluorescent-colored garment. There was no significant interaction of season and garment color. The analyses suggest that color contrast with natural backgrounds might contribute more to the conspicuity of fluorescent red-orange garments than the corresponding luminance contrast. On the other hand, luminance contrast might contribute more to the conspicuity of fluorescent yellow-green garments than color contrast.

research for winter highway maintenance

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