Selection and Application of Warning Lights on Roadway Operations Equipment

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 624

Selection and Application of Warning Lights on Roadway Operations Equipment

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Dr. Ronald B. Gibbons, Group Leader, Lighting and Infrastructure Technology, Center for Vehicle Infrastructure Safety, Virginia Tech, was the principal investigator. Dr. Suzanne E. Lee, also of Virginia Tech, was the co-principal investigator on this project. The other contributors to this project were Mr. Brian Williams, Mr. Michael McNulty, Mr. Gregory Fitch, and Dr. C. Cameron Miller. The work was performed under the general supervision of Dr. Gibbons and Dr. Lee. The work conducted at NIST was performed under the supervision of Dr. Miller.

FOREWORD

By Amir N. Hanna
Staff Officer
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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.

Roadway operations equipment used for construction, maintenance, utility work, and other similar activities generally operate within roadway right of way. These vehicles and mobile equipment operate on all types of roadways, during day and night hours, and under all weather conditions. To improve motorist and work-crew safety, equipment must be readily seen and recognized and, therefore, warning lights are provided on the equipment to alert motorists of potentially hazardous situations. Amber warning lights have traditionally been used although lights of other colors are often added with the intent of helping the traveling public better see the equipment. Combinations of amber, blue, and white lights and other forms of warning lights (e.g., lighted bars, lighted "arrow sticks," strobe, LED, and alternating flashing) are used. There is a concern that this variety of lighting on roadway operations equipment has evolved without adequate consideration of the effects on the awareness and responsiveness of motorists. In addition, there are no widely accepted guidelines for selecting warning lights on roadway operations equipment that consider the type of equipment, weather conditions, day- and night-time operation, color of vehicle, and other relevant factors. Thus, research was needed to develop guidelines to assist transportation agency personnel in selecting and procuring lights that will substantially enhance motorist awareness.

Under NCHRP Project 13-02, "Guidelines for Selection and Application of Warning Lights on Roadway Operations Equipment," Virginia Polytechnic Institute and State University of Blacksburg, Virginia worked with the objective of developing guidelines for selection and application of warning lights to improve the conspicuity and recognizability of roadway operations equipment used for construction, maintenance, utility work, and other similar activities. To accomplish this objective, the researchers conducted a review of current practices for use of warning lights on maintenance vehicles and an investigation to evaluate several aspects of the warning light system. This investigation included photometric characterization, screening, and performance experiments to evaluate lighting parameters that influence system performance as defined in terms of glare and vehicle detectability.

Based on the results of this work, the research recommended guidelines for the selection and application of warning lights on roadway operations equipment, and proposed photometric limits for these warning lights.

The recommended guidelines together with accompanying proposed photometric and technical information provide a basis for developing procurement specifications for warning lights applied to roadway operations vehicles that will provide enhanced conspicuity and recognizability.

Appendixes A through E contained in the research agency's final report provide detailed information on relevant literature, the experiments performed, and data analysis. These appendixes are not published herein but are available on the TRB website at www.trb.org/news/blurb_detail.asp?id=9632. These appendixes are titled as follows:

Appendix A: Literature Review
Appendix B: Identification of Relevant Factors
Appendix C: Photometric Characterization Experiment
Appendix D: Static Screening Experiment
Appendix E: Performance Experiment

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SUMMARY

Selection and Application of Warning Lights on Roadway Operations Equipment

Roadway operations equipment used for construction, maintenance, utility work, and other similar activities generally operate within roadway right-of-way. These vehicles and mobile equipment operate on all types of roadways, during day and night hours, and under all weather conditions. To improve motorist and work-crew safety, equipment must be readily seen and recognized and, therefore, warning lights are provided on the equipment to alert motorists of potentially hazardous situations. Amber warning lights have traditionally been used, although lights of other colors are often added with the intent of helping the traveling public better see the equipment. Combinations of amber, blue, and white lights and other forms of warning lights (e.g., lighted bars, lighted “arrow sticks,” strobe, light emitting diodes [LED], and alternating flashing) are used. There is a concern that this variety of lighting on roadway-operations equipment has evolved without adequate consideration of the effects on the awareness and responsiveness of motorists.

This research project was undertaken to evaluate the effectiveness of warning lights on roadway maintenance vehicles with the goal of establishing guidelines for the application of the lighting system on the vehicle. The research included an evaluation of the lighting parameters that define the performance in terms of glare and vehicle detectability as well as an evaluation of the lighting systems in adverse weather and in a dynamic setting.

Summary of Findings

This research identified several aspects of the warning-light system as critical for vehicle safety; these aspects are reiterated in the proposed guidelines provided as an attachment to the report. The research also showed that a balance must be maintained between the conspicuity and safety of the maintenance vehicle and its crew and the glare imposed on the other drivers. The safety of the maintenance-vehicle crew involves both situations when the crew is in the vehicle and when the crew is outside of the vehicle, possibly working on the road.

The research first identified the requirement for the use of internally illuminated sources and for the warning system to provide active illumination for the safety of the maintenance crew and the driving public. Passive reflectors such as Department of Transportation (DOT) tape did not draw the driver’s attention or provide any attention-getting cues to an approaching vehicle.

Flashing lights were found to be more conspicuous than continuous lights and provide a sense of urgency. An asynchronous flashing pattern (flashing side to side) provided a higher attention-getting rating than a synchronous flash pattern (both sides flashing at once). Amber light sources and white light sources provided higher responses than blue or red. With regard to the relationship of the light color to the vehicle type, amber and white are more related to maintenance vehicles than the other possible colors that are closely tied to police and fire services.

The research also showed that light sources with a higher effective intensity will provide higher attention-getting than a light source with a lower effective intensity, although this effect is offset by the flash characteristics. A warning-light system that provides a different flash pattern than the other lighting systems in the road environment improves the ability of the driver to identify the vehicle sooner. Using a double flash or varying the effective intensity (such as with a rotating beacon) allows the maintenance vehicle to be identified at a longer distance than other flash patterns. Also, when approaching a vehicle from the rear, drivers primarily use the vehicle's tail lights for vehicle identification; locating the warning-light system high on the vehicle away from the tail lights improves vehicle identification distance.

The research showed that a warning-light system must have a higher effective intensity during the daytime in order to provide adequate daytime conspicuity. This intensity may vary by the type of light source used. The research further showed that a warning-light system with halogen lamps may provide a higher conspicuity at a lower effective intensity than warning lights using LEDs. Because there is no evident glare in the daytime environment, no maximum effective-intensity limit is suggested. Another issue relevant to daytime conspicuity is the location of the light source. A warning light seen against the sky will have reduced contrast and conspicuity compared to a warning light seen against a dark background. Therefore, the light must appear against a controlled background in order for the conspicuity to remain constant.

The research showed that the sources used to provide adequate daytime conspicuity will cause significant glare for opposing and passing drivers at night. Adequate conspicuity can be provided at night with a much lower effective-intensity level. Therefore, effective intensity of the lighting system must be maintained between the level that provides conspicuity and the level that does not cause too much glare. The photometric effective-intensity values describing these limits are discussed below.

A higher effective-intensity light source was found to limit the detection of a pedestrian around a vehicle, thus, negatively affecting the safety of the maintenance crew when they are outside of the vehicles. This factor limits the overall effective intensity that should be used for the warning-light system. Using too many lights or lights with too high an effective intensity may impede the ability of other drivers to detect a pedestrian.

The potential for glare is the primary consideration when specifying requirements for warning lights that will be used during nighttime. Bright warning lights and oppressive flashing will provide disability glare and discomfort for a driver of an oncoming vehicle or a vehicle passing a maintenance vehicle from behind. Glare from the warning-light system may limit the ability of the driving public to travel safely.

Glare is primarily a result of the effective intensity of the light source. The research showed that a light source with a higher effective intensity creates a greater glare response than a light source with a lower effective intensity. Glare and pedestrian detection distance also provide a limit to the maximum effective intensity of the warning-light system. This factor will further limit the number and type of light sources placed on the maintenance vehicle.

The position of the warning lights also affects glare. The research showed that a light positioned close to the height of an opposing driver's line of sight creates a greater glare response than a high-mounted lighting system. This response is particularly evident with 360° sources (lights that are seen from all angles), as a passing driver will be able to see that source even if the driver is very close to the maintenance vehicle. This consideration supports a requirement to locate the lighting system as high as possible on the vehicle.

Adverse weather conditions impact visibility of maintenance vehicles. The research showed that the vehicle identification distance is diminished in adverse weather conditions. The presence of moisture in the atmosphere will cause absorption of the light from the warning system and will cause the light to scatter. In this research, the low-visibility condition was tested using fog as a surrogate for snow. In the experiments, a higher effective intensity caused both a greater amount of scatter and, therefore, a greater glare experience at night. However, the higher effective intensity improved the visibility of the vehicle. The effective intensity is limited by the glare in this condition and additional lighting in adverse weather will likely cause difficulties to opposing and passing vehicles.

The research showed that in a visually complex environment, a higher effective intensity may be required for adequate performance as compared to simple rural environments. Also, glare ratings were lower on a road with an overhead lighting system and opposing traffic than on a rural test track. Similarly, the high-effective-intensity light source caused passing vehicles to change lanes earlier than they did in the presence of a low-effective-intensity light source. When other vehicles were present, the glare ratings were also reduced. In visually complex environments, it may be possible to use a higher effective intensity to provide increased visibility of the vehicle while not causing too much glare for other drivers.

Lighting Requirements and Considerations

The recommended lighting requirements are based on the results of the experimental investigation and requirements for safety of the vehicle and other drivers.

Light Source Selection

There seems to be no benefit of one light source over another in general use. Because the spectral output of the source is very pure, solid-state LED sources seem to provide a benefit with some colors. LED sources also provide an equivalent amount of light at a reduced wattage that may be beneficial to the vehicle in terms of electrical system loading. Many of the visual effects of the low- and high-mounted beacons can be achieved using LED light sources.

Signal Colors

It is recommended that only amber lighting and white lighting be used in maintenance vehicles, with amber being the predominant color. These colors provide increased detectability and are least confused with other on-road activities such as law enforcement and emergency response.

Light Type Selection

Flashing Lights

It is recommended that the predominant light pattern be flashing. A pattern that alternates from one side of the vehicle to the other is preferable to one in which lights on both sides of the vehicle are flashing at the same time. It is also recommended that a slower flash frequency be used, because there was better response to the longer flash durations than to shorter flash durations. A flash pattern such as a double flash or a pattern similar to a rotating beacon will provide an appearance that enables vehicle identification and should improve response. A rotating beacon will provide the appearance of flashing, and when two beacons are used, it is rare for them to appear synchronized.

Steady Light

It is recommended that, if a steady (continuous burning) light is used on the vehicle in order to meet the federal vehicle lighting requirements, it should be used only as a supplement to the flashing-light systems. Because regulations are subject to change, the most recent federal statutes (e.g., Federal Motor Vehicle Safety Standards [FMVSS] 108) should be consulted when designing a lighting system. Steady lights have many other vehicle uses, such as clearance indicators, brake lights, and vehicle headlights, and thus they should not be used to warn drivers of the presence of maintenance vehicles.

Lighting Layout and Positioning

In the layout of the vehicle lighting, positioning the lighting such that it appears against a portion of the vehicle and not against the sky will provide a consistent contrast and will allow for increased daytime and nighttime conspicuity. However, this configuration limits the ability of the light to be seen from all directions. For example, a rotating beacon placed on top of a vehicle will lose some of its conspicuity when viewed against a daytime sky, especially with the sun behind it. This effect can be mitigated by use of flat-mount LEDs or strobe lights mounted against a solid surface. It may thus be necessary to replicate the lights at the front, sides, and back of the vehicle.

The lighting system should be positioned such that the light does not cause excessive glare to approaching and passing drivers. The light should also be placed away from the tail lights of the vehicle to allow those lights to be seen (i.e., mounted high on the vehicle above the typical eye height of other drivers) and in a manner that will outline the vehicle (i.e., on either side of the vehicle and on any portion of the vehicle which extends beyond the lane such as a plow blade or a trailer extension).

Retroreflective Tape

It is recommended that retroreflective tape be used as a supplement to a flashing warning-light system. This material can be used to identify vehicle shape, but should not be used as the only notification system on the vehicle.

Effective-Intensity Requirements

The effective intensity of the warning-light system is limited at a minimum in terms of the conspicuity of the maintenance vehicle and at a maximum by the glare apparent to other drivers. The research showed that the nighttime and daytime requirements are different and may require two alternative warning-light systems, or a method of automatically attenuating the daytime levels in the presence of dark conditions. The effective-intensity measurements used in this research are based on the Form Factor method for calculating effective intensity. The recommended values represent the total light output limits for the warning-light system. A higher effective intensity may be required for vehicles that are primarily used in urban and visually complex environments.

CHAPTER 1

Introduction and Research Approach

Background

Roadway operations equipment used for construction, maintenance, utility work, and other similar activities generally operate within the roadway right-of-way. These vehicles and mobile equipment operate on all types of roadways, during daytime and nighttime hours, and under all weather conditions. To improve motorist and work-crew safety, equipment must be readily seen and recognized; therefore, warning lights are provided on the equipment to alert motorists of potentially hazardous situations. Amber warning lights have traditionally been used, although lights of other colors are often added with the intent of helping the traveling public better see the equipment. Combinations of amber, blue, and white lights and other forms of warning lights (e.g., lighted bars, lighted "arrow sticks," strobes, light emitting diodes [LED], and alternating flashes) are used. There is a concern that this variety of lighting on roadway operations equipment has evolved without adequate consideration of the effects on the awareness and responsiveness of motorists.

There are no widely accepted guidelines for selecting warning lights on roadway operations equipment that consider the type of equipment, weather conditions, daytime and nighttime operation, color of vehicle, or other relevant factors. Research was needed to develop guidelines for use by transportation agency personnel in selecting and procuring lights that will substantially enhance motorist awareness. NCHRP Project 13-02 was conducted to address this need.

Objective

The objective of this research was to develop guidelines for selection and application of warning lights to improve the conspicuity and recognizability of roadway operations equipment (i.e., vehicles and mobile equipment) used for construction, maintenance, utility work, and other similar activities. This objective was accomplished through the following tasks:

1. Collection and review of relevant literature, specifications and guidelines, research findings, current practices, government requirements, and other information relative to selection and application of warning lights on equipment used in roadway operations. Motorist response and other criteria used in the selection process were also identified and discussed. This information was assembled from published and unpublished reports, contacts with transportation agencies and industry organizations, and other domestic and foreign sources.
2. Identification and discussion of the factors related to the design and selection of warning lights. These factors included type and purpose of vehicle; daytime and nighttime operations; weather conditions (e.g., snow, rain, fog, and dust); light details (e.g., color, type of light source, configuration and effective intensity of lights, flash patterns and parameters, location of lights on vehicles, and durability); color of the vehicle and markings on it; and distinguishability from emergency response vehicles.
3. Assessment of the relevance and importance of the identified factors to the selection and application of an effective lighting system, development of a prioritized list of these factors, and recommendation of specific factors for further research.
4. Preparation of a detailed work plan that included experimental investigations for addressing the recommended factors and developing the guidelines.
5. Conduct of the recommended investigations and development and validation of the guidelines for the selection and application of warning lights on vehicles and mobile equipment used in roadway operations. The guidelines also included the technical information necessary for developing procurement specifications. This task was composed of the photometric evaluation of the light sources, and static and dynamic human factors tests.
6. Submittal of a final report that documented the entire research effort.

Report Organization

This report documents the work performed in this project. Chapter 1 describes the research approach and summarizes the findings of the literature review. Chapters 2, 3, and 4 describe the photometric characterization, the static screening, and the performance experiments, respectively. Chapter 5 provides conclusions and suggested research. A more in-depth discussion of the experiments is included as appendixes to this report (not published herein but available on the TRB website at www.trb.org/news/blurb_detail.asp?id=9632).

Trade or manufacturers' names appear in the report solely because they are considered essential to the object of this report.

Literature Review

Currently, there is a wide disparity in the design of warning lights used on roadway maintenance vehicles. The Manual on Uniform Traffic Control Devices (MUTCD) provides some guidance for the use of traffic control, signage, and auxiliary safety vehicles, but these recommendations are not specific as to the nature of the lighting on the vehicles themselves. Recent studies have highlighted the lack of specific criteria for the use of warning lights. Kamyab and McDonald (*1*) found that there is a great disparity among states in the use of warning lights and that disparity exists even within local agencies.

Several studies have also investigated different aspects of lighting systems, from color to configuration, but no single study has been undertaken to provide comprehensive guidelines for the marking of maintenance vehicles. Because many types of maintenance vehicles are required to operate in bad weather environments and during both daytime and nighttime, these environments are particularly critical aspects of the warning-light guidelines. A more detailed literature review is provided in Appendix A.

Hazard Detection and Recognition

Hazard detection refers to the first stage of information processing in which an object is perceived by one's senses. Hazard recognition refers to a later stage of information processing in which drivers use their memories to relate the object to previous experiences. Recognition typically involves mental operations (or attention) and as a result takes longer than detection. However, certain characteristics of objects can support pre-attentive processing, or recognition without the application of attention.

Contrast sensitivity is a main determinant of one's ability to detect objects of interest in a visual scene because the human eye emphasizes regions of differences in illumination—because they possess the most information.

Detection and recognition of objects in the road is context dependent. Drivers scan the roadway by looking in the direction they expect to see an object of importance. Cox (*2*) points out that warning-light placement faces the following constraints in terms of capturing attention:

- Motorists make multiple decisions on proximal events while driving. As a result, distant low-effective-intensity lights may not be detected since they have no immediate interest.
- Drivers' eyes are cast downward in the natural human posture. As a result, drivers do not naturally keep a special lookout for distant objects.
- A meaningful proportion of motorists is colorblind or has poor visual acuity.

Conspicuity

The conspicuity of an object, which refers to how well it captures one's attention, comes in two types: attention conspicuity and search conspicuity. Attention conspicuity is attributed to an object's characteristics, such as proximity, color, and movement. Search conspicuity refers to an object's ability to capture one's attention when one is actively searching for it, such as a retroreflective street sign placed in a consistent location (*3*).

Because the presence of a maintenance vehicle is unexpected, vehicles that have poor attention conspicuity are less likely to be detected at a safe distance because motorists are not actively searching for them.

Detection and recognition of unexpected events have further implications than simply attention conspicuity. The next section explains why response time to unexpected events is longer than that to expected events.

Reacting to the Unexpected

Whenever individuals respond to events that have been perceived, they are transmitting information. Information is defined by Shannon and Weaver (*4*) as the reduction of uncertainty. Information is potentially available in an event any time there is uncertainty about what the event will be. Information theory states that the uncertainty of an event is dictated by the number of possible events that can occur, the probability of each event occurring, and the context or sequential constraints that relate each event together (*5*).

Dewar and Olson (*6*) explain that motorists operate with a set of expectancies, predisposing them to believe that things will happen in a certain way. There is an increase in driver perception-response time when the expectancies are violated; this increase can lead to increased driver errors and crashes. To account for these predispositions, advanced warning signs are used with the intention of establishing expectancy for upcoming hazardous conditions. However, when confronted with unexpected events, motorists require assistance in coping with the change in task demands. A form of guidance, termed positive guidance, has been developed to aid people in such situations.

Positive Guidance

Positive guidance (*6*) is a way of providing information to allow the driver to detect a hazard in a roadway environment that may be visually cluttered, recognize its threat potential, select an appropriate speed and path, and complete the required maneuver safely. The positive guidance concept acknowledges three levels of driver performance: control, guidance, and navigation (*6*).

Control. The control level encompasses the interaction between the driver and the vehicle. Drivers control vehicles through the steering wheel, accelerator, and brake.

Guidance. The guidance level describes the selection and maintenance of a safe speed and path. Dewar and Olson (6) state that information at the guidance level comes from the highway, traffic, and traffic control devices.

Navigation. The navigation level refers to the planning and execution of a trip from origin to destination. Decisions at the navigation level are made at select points based on information extrapolated from maps, verbal directions, experience, guide signs, and landmarks.

Information Placement

Dewar and Olson (*6*) also explain that, to execute positive guidance in traffic control devices, four principles of information placement must be followed: primacy, spreading, coding, and redundancy. Primacy requires information on signs to be placed according to importance to the driver. Spreading requires information content to be spread out across multiple signs when its content is too great to place on one sign. Coding requires pieces of information to be organized into larger units (e.g., using specific colors and shapes for street signs). Redundancy requires information to be presented in more than one way at the same time (e.g., an emergency vehicle's visual warning lights and auditory siren).

Flashing Warning Lights

Flashes are bursts of light which, by definition, are unexpected because they do not occur in nature (save for lightning). This characteristic is their most important feature and why they are so good at capturing attention. Holmes (*7*) suggests that flashing lights have their own language. The flash's characteristics (such as flash frequency, effective intensity, and duration) are elements of a language that can be learned. Holmes also suggests that people need to be educated on how to recognize flashing signals (because they are artificial) and how to interpret their meanings.

The characteristics affecting warning-light conspicuity include contrast brightness, flash effective intensity, flash color, flash frequency, flash duration, flash shape, flash type, flash pattern, flash size, number of elements, and apparent motion, and steady-burn light color.

Contrast Brightness

Contrast brightness refers to the direct comparison of one reflecting surface with another. Contrast brightness of a flashing light signal is obtained from the difference in illumination between the lamp-illuminated bulb, called a "roundel," and the background.

Flash Effective Intensity

Roufs (*8*) defines flash threshold as the minimum effective intensity increment required for perceiving the flash. For short flashes, the threshold is driven by the product of the flash effective intensity and duration. The threshold for long flashes is mainly determined by the effective intensity.

Flash Color

Cook et al. (*9*) investigated the conspicuity of warning beacons according to flash color and found that when effective intensity is held constant, amber has the poorest detection time under both day and night conditions. Blue light minimizes the effects of disability glare and daytime discomfort glare. Green light has the quickest detection time during day conditions, but is the poorest for disability glare and discomfort glare. Red light yields the quickest detection times and gives rise to the least discomfort glare.

Flash Frequency

Misinterpreting flashing lights designed to communicate a message to motorists can be as dangerous as missing the signal. To avoid misinterpretation, the flashing light signal must be seen for the duration of one period. Holmes (*7*) states that the flashing signal should be repetitive and have a maximum interval of 5 s to continuously retain the observer's attention.

Flash Duration

The flash duration is defined as the length of time during which the light is on in one flash cycle. Brown and Gibbs (*10*) found that, as the flash frequency duration decreased for frequencies in the range of 1.5 to 3 Hz, there was a corresponding decrease in reaction times. However, for signals with frequencies of 1 Hz and 0.33 Hz, Gerathewohl (*11*) found that longer flash durations yielded shorter reaction times.

Flash Shape

The flash shape refers to the temporal distribution of light in the flash cycle. Howard and Finch (*12*) state that for flashes that last longer than the critical duration of 50 ms, the square wave pattern is more effective than a triangle shape wave of equal flash energy.

Flash Type

Cook et al. (*9*) investigated the conspicuity of warning beacons according to flash type. They found that strobe warning beacons were subjectively considered to convey greater urgency, while rotating warning beacons were considered to be less annoying and minimized the effects of disability glare.

Flash Pattern

Cook et al. (*9*) also investigated the conspicuity of warning beacons according to flash pattern. They found that when more than one warning beacon was present on a vehicle, beacons that flashed simultaneously were detected significantly faster than beacons that flashed alternately. Simultaneously flashing beacons were also subjectively rated as more conspicuous, while those that flashed alternately had the lowest discomfort glare.

Signal Size

Many investigations on steady lights at threshold levels have concluded that lamp size does not play a significant role in determining its conspicuity. However, the perception of light under road conditions is quite different than under laboratory conditions. Cole and Brown (*13*) concluded that effective intensity is independent of signal size for light signals with a high probability of being seen (called optimum signal luminance) and that, if the lamp is of optimum luminance, its size does not matter.

Number of Lights

Cook et al. (*9*) investigated the conspicuity of warning beacons according to the number of elements utilized. From subjective ratings, they found that the greater the number of warning beacons, the greater the perceived conspicuity.

In 1990, Hanscom and Pain (*14*) developed guidelines for warning-light systems on service vehicles engaged in short-term or moving maintenance operations. Based on the results of both a closed-field and field experiment, the following conclusions were made:

- If only one type of light is used, four-way flashers provide the most accurate information about closure rate and service vehicle speed.
- Adding more of the same type of lights does not increase the amount of information provided to the driver or enhance the driver's ability to extract information from the lights.
- Changing the location of the light(s) does not increase the information or ability to extract information; it is important that the light can be seen from all directions.
- Lighting parameters had little effect on driver response.
- Adding a four-way flasher to any other warning light increases the amount of information provided to the driver, and combining a roof-mounted flasher light and rotating light increases the information to the driver.

Apparent Motion

Under certain conditions, it is possible to create a sense of motion between two stationary sources of light by flashing the two lights on and off with one source temporally trailing the other. Foster (*15*) showed that a model developed to describe certain real-motion effects also translated to describe the existence of an apparent-motion effect.

Steady-Burn Light Color

Color is an established coding dimension for inter-vehicle signaling. Projector et al. (*16*), however, reject the use of color-coding owing to variation in observer vision, desaturation of colors in haze and fog, and variation in filter efficiencies, but note that color is useful as a redundant perceptual dimension.

Hazard Analysis

In investigating the effective conspicuity of new warning lights, factors that present potential drawbacks must also be considered. Disability glare, discomfort glare, distraction, and eleptogenic response are such factors.

Disability Glare

Disability glare occurs when a bright light source impairs an individual's ability to see objects. The effect of disability glare caused by warning beacons, as stated by Cook et al. (*9*), was assessed by subjects' ability to detect a pedestrian in their vicinity. They found that disability glare was worsened by amber beacons, strobe beacons, and maximum intensities.

Discomfort Glare

Discomfort glare is defined as glare that is annoying or painful, but that does not cause impairment in the visual field. Discomfort glare could potentially have safety implications because it may cause drivers to avert their gazes. Cook et al. (*9*) found that discomfort glare was worsened by amber and green beacons, strobe beacons, maximum flash frequencies, and simultaneous flash frequencies.

Distraction

A balance needs to be made between warning-beacon conspicuity and warning-beacon distraction. Cook et al. (*9*) found that the presence of a warning beacon is significantly more distracting than no warning beacon at all, but the extent of the distraction was not related to flash type, frequency, or effective intensity.

Eleptogenic Response (Epileptic Seizure)

Some features of flashing lights, such as flashing light frequency, luminance, field of view, and flash type, are relevant to eleptogenic response. Frequencies above 5 Hz should be avoided. Luminance as low as 20 cd/m^2 can trigger eleptogenic response; however, this exceeds the luminance required to make a warning beacon conspicuous. Lights flashing in the center of the visual field are more likely to cause an eleptogenic response. Also, drivers of emergency vehicles reported that strobe beacons cause more visual discomfort than rotating beacons.

Environment Complexity

Hargroves (*17*) states that the background has a significant effect on the conspicuity of flashing lights. Day, night, glare, and irrelevant lights can affect the conspicuity of the flashing-lights signals.

Number of Irrelevant Lights

Crawford (*18*) found that response times to light increase from 0.8 s to almost 2 s when 21 lights are added to an otherwise clear background in a dark soundproof room. He also showed that steady signals are always more effective than flashing ones if the proportion of flashing background lights exceeds 1 in 10, and therefore, overuse of flashing lights would defeat their purpose.

Time of Day

For a fixed luminance, a warning light will have a further detection distance during the night than it will during the day because the contrast of the signal is great at night.

Weather

The presence of snow, rain, or fog interferes with the percentage of light reaching the driver's eyes from the warning light. When the brightness is decreased, the signal is harder to detect.

Road Geometry

Because the human eye's sensitivity to light is dependent on location of the light within the retina, it is possible that the placement of the warning light in the visual scene as a result of the road geometry will have an effect on its conspicuity. The geometry of the road, combined with the obstruction of lights from trees, rocks, and buildings, may affect the conspicuity of the warning lights.

State Practices for Roadway Warning Lights

The application of warning lights to maintenance vehicles differs among highway agencies in the Untied States. Warning-light specifications for some state departments of transportation are presented in this section. These differences highlight the need for developing guidelines that will have nationwide applicability.

Virginia

The Virginia Work Area Protection Manual (*19*) specifies the design and application of temporary traffic control devices. The manual states that warning lights should be either a rotating amber light or high-effective-intensity amber strobe light, and that rotating lights shall be mounted to be viewable for 360° among other specifications of intensity, flash frequency, etc.

Ohio

The Ohio Department of Transportation (ODOT) (*20*) established a vehicle warning-light policy to assure the districts and Central Office maintain uniform lighting array, equipment light, marking, and conspicuity. This policy states that all safety lighting will be flashing lights; amber in color; composed of photo strobes, LEDs, or a combination of both; and viewable from 360°.

New York

The New York State Department of Transportation (NYSDOT) follows a vehicle marking and lighting standard that was developed in the mid-1980s. Few recommendations have been made to improve upon the standard; one change that has been implemented is the use of more LED lights for tail lights and marker lights to reduce power draw and increase visibility. The DOT believes that the halogen rotating yellow beacon provides the best overall light for visibility and safety for the traveling public.

Maine

The Maine DOT (MDOT) does not have a traffic engineering handbook, but amber lights are used on all of their construction vehicles; state law precludes the use of red or blue.

Iowa

The Iowa DOT conducted an investigation on the types of crashes involving snowplows and concluded that the rear end of the snowplow needs to be more visible to give approaching vehicles more time to respond. The snowplows currently use two amber rotating beacons and two amber rear-directional alternate flashing strobes (*21*). Retroreflective tape, warning flags, and auxiliary headlamps are also used as warning devices.

Texas

Texas DOT adopted a warning-light policy for use on specified vehicles and equipment based on research conducted at the Texas Transportation Institute (TTI) in 1998 (*22*). Amber warning lights are used to identify highway maintenance and service equipment.

Flashing Light Measurement Issues

In the 19th century, it was recognized that intermittent light, or flashing lights, produced higher visibility than a steady light of the same intensity. Thus, efforts began to quantify the visibility as effective intensity. Effective intensity is defined as the luminous intensity of a fixed (steady) light, of the same relative spectral distribution as the flashing light, that would have the same luminous range as the flashing light under identical conditions of observation (*23*). A singular equation has not been developed, but several options for calculation exist, including the Allard (*24*), modified Allard (25), Blondel-Rey (*26*), Blondel-Rey-Douglas (*27*), and Form Factor (*28*) methods.

Retroreflective Tape

During the winter months, detection and recognition of snowplows can be deterred by the snow cloud produced by these vehicles. Because the cloud of snow covers the tail light and makes detection of such vehicles even harder at night, the use of retroreflective strips has been considered. A study conducted by TTI found that the 8-inch-wide orange and fluorescent-orange magnetic strips had an insignificant impact on daytime driving, but could improve the visibility of vehicles during nighttime or low-visibility winter weather (*21*). Morgan (*29*) found that retroreflective tape reduced side and rear impacts into trailers in dark conditions.

SAE Standards

The Society of Automotive Engineers (SAE) released a standard for the lighting and marking of industrial equipment on highways (J99) in March 1999 (*30*). The standard states that there shall be at least two amber flashing warning lamps spaced as laterally wide as practicable and mounted at the same level at least 42 in. high as measured from the lamp's axis.

SAE also developed SAE J2040 (*31*) in 2002 to specify the requirements for tail lights placed on vehicles of widths of 2032 mm or wider. The standard states that the color of the tail light shall be red and should have an effective projected luminous lighted lens area of at least 75 cm^2.

Survey of Current Equipment Available

There are many products on the market with similar photometric characteristics, and the information provided to consumers is often confusing. Three technologies of flashing equipment are available. The difference among these technologies is the source of the light: incandescent filament bulb, xenon or high intensity discharge (HID) flash tube (commonly referred to as strobe lights), and LED. However, because no classification system currently exists, the lighting must be judged on the source technology only.

Incandescent Filament Bulb

There are two types of flashing lights that use incandescent filament bulbs: rotating beacons and 360° flashing lights. The pulse width and shape of a rotating beacon are determined by the reflective optic because the bulb is on continuously. The wattage of the bulbs describes the quantity of light available to the system, but the shape and efficiency of the reflector is what controls the pulse intensity and width. The 360° flashing light ramps the current up and down quickly to create the time dependence. A dome with a Fresnel lens encases the lamp and focuses the light in the plane of the observer.

Xenon or HID Flashtubes

The xenon or HID flashtube lamps have a similar structure to that of the 360° flashing lights with a Fresnel dome encasing the flashtube light source. A significant difference between the flashtube and incandescent filament sources is the peak instantaneous intensity and pulse width. The peak instantaneous intensity can be 1000 times more, but the pulse width is usually 1000 times less in width.

LED-Based Lamps

Many systems that use yellow LEDs as a light source are now available. A few are based on the 360° flashing-light assembly, but many are strictly for directional purposes. It is likely that more of these assemblies will replace the 360° or rotating assembly in the future because of the electric efficiency.

Literature Review Conclusions

Because the presence of maintenance vehicles on the road is an uncommon event with low probability, motorists consider their encounters with maintenance vehicles to be unexpected events. Any measure that increases the distance at which motorists are informed about the presence of maintenance vehicles will increase the time available to react. Because signs are stationary countermeasures and the operation of shadow vehicles is expensive, the use of more conspicuous warning lights is desired.

The literature review provided guidance on which factors (e.g., light color, types of lights, ambient lighting, lighting intensity, driver factors, the use of flashing, etc.) should be considered in developing guidelines for the use of warning lights and therefore should be considered in this research. However, it did not provide final answers on the relevance of these factors to particular applications.

Identification of Relevant Factors

Based on the results of the literature review, a prioritization of the relevant factors was conducted by surveying knowledgeable practitioners. As an initial evaluation, the factors were characterized as lighting factors, vehicle factors, environmental factors, and driver factors. Of these factors, only lighting and the vehicle factors are controllable by the responsible agency.

Through the survey, the lighting factors were found to be most critical, followed by the environmental and driver factors. The vehicle factors were not regarded as important as the others.

Based on these findings, an experimental program was developed that included an initial screening experiment to reduce the number of lighting factors to be considered followed by a dynamic experiment in which the weather conditions could be investigated.

A complete description of the relevant factors and the knowledgeable practitioner survey is provided in Appendix B.

CHAPTER 2

Photometric Characterization Experiment

The purpose of this experiment was to photometrically characterize the light sources that are typically used in warning-light conditions. The photometric measures include the color characteristics and the effective-intensity characteristics. A more detailed description of the experiment and the results is provided in Appendix C.

Experimental Method

The photometric characterization of the light sources was performed on 35 different devices. However, with alternative flash patterns, over 135 different flash patterns have been investigated. The purpose of this work was to identify suitable light sources to be used in the screening and the dynamic experiments. The technologies used in these devices included rotating beacon, strobe, halogen, and LED. The data measured for each device included time-averaged chromaticity, time-averaged luminous intensity, repetition rate, and waveform. These measurements were made at the Center for High Accuracy Retroreflection Measurements (CHARRM) facility of the National Institute of Standards and Technology (NIST). The photometer was capable of positioning the devices 0.5 to 30.5 m away from the light detector.

Data Analysis

For each light source, the time-averaged chromaticity, the time-averaged intensity, and the effective intensity were calculated. The effective intensity was calculated for each of the flashing lights using four of the previously mentioned methods (Allard, modified Allard, Blondel-Rey-Douglas, and Form Factor). The spectral waveform and the time-based waveform were also included in the analysis.

Summary of Results

To summarize the data, the results of the measurements were characterized by the lamp type and the color. Figure 1 shows effective intensity calculated by each of the four methods. With the exception of the strobe lights, the results showed fairly similar patterns, with the values from the Form Factor method being just slightly lower than values from the Allard method, followed by the modified Allard and the Blondel-Rey-Douglas methods. For the strobe systems, the Form Factor method provided much higher values than the other methods. It was also notable that the blue and red lights had lower excitation levels than the amber and white for all of the light sources tested, and the LED had significantly lower values than the halogen and the strobe.

Color characterization of the sources was also considered. The colors for the red and the amber light sources all match fairly closely, but the blue and the white colors were very widely dispersed.

Based on these measurements, the relationship of the measured data to the human response was considered. The most appropriate metric was determined through the correlation of the response and the photometric data.

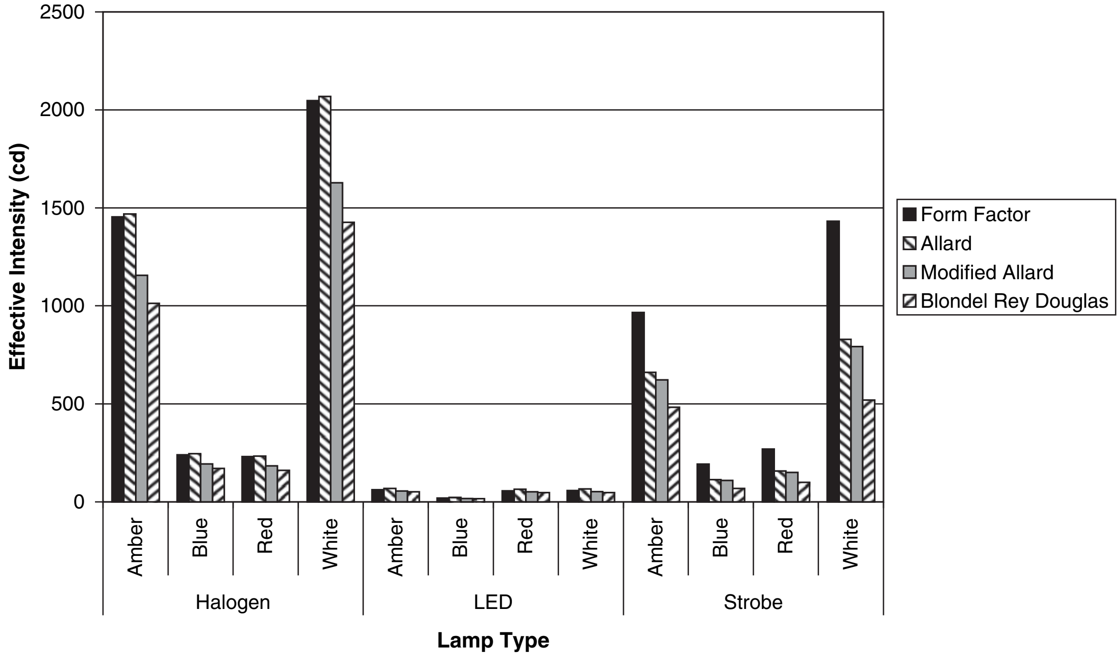

Figure 1. Effective-intensity calculation by all four models.

CHAPTER 3

Static Screening Experiment

The results of the literature review and survey were used to develop and conduct a static screening experiment in which 41 lighting configurations were tested in daytime and nighttime with regard to attention-getting, discomfort glare, meaning, and ability to detect using peripheral vision. The lighting conditions of color, intensity, flash pattern, and lamp type were all investigated in this experiment using human participants in a static (stationary vehicle) test scenario. The four lighting configurations were then carried forward into a dynamic experiment. A complete description of the experimental methods and the results is included as Appendix D.

Experimental Methods

Experimental Design

The choice of independent variables (factors that were manipulated during the experiment) was driven by factor rankings suggested by the knowledgeable practitioners described in "Identification of Relevant Factors" in Chapter 1 and shown in Appendix B. Variables considered included between-subjects variables (gender and age, each with two levels) and within-subject variables (intensity with two levels, format with five levels, contrast with two levels, flash pattern with four levels, color with four levels, and position with two levels). Because of the large number of identified variables, a mixed-factor partial factorial design was used to allow exploration of the most relevant main effects and interactions. In other words, because it was not feasible to present every participant with every possible combination of the independent variables in the time allotted, only the most relevant combinations were used. The final experiment design resulted in a total of 82 conditions for each participant: 41 during the day, and 41 during the night. The daytime and nighttime conditions were essentially the same except for time of presentation.

Format, Intensity, Color, and Flash Pattern

LED and Halogen Panel Lights. The LED and halogen panel-mounted lights were only capable of illuminating at one intensity setting. The high-intensity condition was achieved by activating two adjacent lights at once, which then flashed simultaneously (for the flashing conditions). Using a light controller, four different flash patterns were tested: (1) steady, (2) synchronous at 1 Hz (the light or lights on each side flashing at the same time at 1 time per second), (3) asynchronous at 1 Hz (the lights or lights on each side flashing in an alternating pattern), and (4) asynchronous at 4 Hz. The two intensities and four light patterns made up eight conditions. Four colors were also tested (red, blue, amber, and white), adding an additional six conditions. The lighting panel layout did not allow both of these types of lights to be mounted at once; therefore, half of the participants received the LED-light conditions and half received the halogen-light conditions. Each participant received the same condition (LED or Halogen) at both nighttime and daytime.

Strobe Panel Lights. The strobe lights mounted on the panel were capable of being set at two different intensities (low and high). The high-intensity condition was achieved by activating two adjacent lights at once, which then flashed simultaneously. Two flash patterns were selected to test these three different intensities. The first pattern was a double flash, while the second pattern was a quad flash. The same four colors were tested (red, amber, blue, and white).

Rotating Beacons. The rotating beacons selected for this study were capable of rotating at two speeds (slow and fast, equating to two flash patterns) and had two intensity settings (low and high). The rotating beacons were tested with four colors (red, amber, blue, and white).

Passive Format. The passive condition refers to the use of retroreflective tape on the black test panel. Two strips of retroreflective tape were positioned on either side of the test panel at 90° angles. They were covered when they were not being tested.

Location

"Daylighting" refers to placing the lights on top of the black panel in order to test how well they can be seen against the sky. In comparison, placing the lights on a shelf in front of the black panel might increase their conspicuity because of increased contrast. One strobe beacon, one halogen beacon, and one LED beacon were tested both on top of the panel and on a shelf in front of the panel. All beacons either rotated or gave the impression of rotation by sequential activation of lights.

Randomized Assignment of Treatment Orders

Treatment orders were randomly assigned to participants to reduce variation in responses that may have arisen from factors not considered in the experiment, such as fatigue. Six random orders were used for the 24 participants. Subjects were tested during the daytime before being tested at nighttime.

Dependent Variables

Five dependent variables (those factors measured during the experiment) were used in this experiment. The daytime and nighttime attention-getting ratings measured how well the lighting conditions caught the participants' attention. The horizontal maximum peripheral detection angle was measured only during daytime conditions, while the recognition and glare rating dependent variables were measured only at nighttime.

Attention-Getting. To establish the effectiveness of the lighting and marking configuration, a metric for attention-getting was developed. This metric used a seven-point rating scale ranging from "not at all attention getting" to "extremely attention getting"; it was administered in both the daytime and nighttime tests.

Horizontal Maximum Peripheral Detection Angle. The horizontal maximum peripheral detection angle measured the maximum horizontal angle at which the warning light could be detected (in other words, how well the lights could be seen using peripheral vision). Subjects were asked to look at predetermined positions located 15° apart (from 0° to 90° away from the forward view) and state whether they could detect the warning light. The progression of detection angles was conducted both going up (further away from the forward view) and going down (closer to the forward view), and three responses were then averaged. Discrepancies of more than 30° among the three responses were retested. This test was only conducted in the daytime, when contrast of the lights was at its lowest (this represents the worst situation for detecting lights using peripheral vision).

Recognition. The recognition dependent variable investigated how subjects classify the warning-light scheme relative to a list of typical vehicle functions. This questionnaire was only administered at night, when the reaction was expected to be more due to the lights (number, type, arrangement, and color) than to external cues such as the vehicle type holding the lighting panel.

Glare. The glare dependent variable measured the discomfort subjects experienced when presented with the warning-light configurations. A nine-point rating scale ranging from "not noticeable" to "unbearable" was used to capture the ratings. This scale was administered only at nighttime, when discomfort glare is at its worst because of the high degree of contrast between the lights and their background.

Participants

Twenty-four subjects, 12 males and 12 females, were selected to participate in this study. The subjects were evenly represented in two age groups of 25 to 35 years old (younger) and 65+ years old (older). Institutional Review Board (IRB) approval for the use of human participants was obtained prior to recruiting subjects. Once subjects arrived for the first session, they read and signed an informed consent form before beginning any experimental activities. Subjects were paid $20/h, and they were allowed to withdraw at any point in time, with payment adjusted accordingly.

Apparatus

Test Road

The experiment took place on a bridge to an unfinished highway adjacent to the Virginia Tech Transportation Institute (VTTI) and the Virginia Smart Road. A degree of control was attained by not allowing public vehicles and pedestrians to enter the bridge. However, participants could see passing traffic on a lower-level highway during nighttime conditions.

Test Vehicles

A Virginia Department of Transportation (VDOT) no-longer-in-service dump truck was obtained for this experiment. A large panel was used to mount the different lighting configurations; the panel was attached to the rear of the dump truck (Figure 2). Small shelves were used to place the beacons on the lower shelf position during the testing.

Rotating beacons placed on the top of the panel.

Rotating beacons placed on shelves.

Figure 2. VDOT dump truck outfitted with warning lights.

For each grid of lights, the two left-most columns housed LEDs (or halogens for one-half of the participants), while the two right-most columns housed strobe lights. The LED and strobe lights were thus evenly spaced between the left and right side, and to the subject viewing them from 400 ft, their location in space appeared to be the same. All lights were manually controlled by an operator who sat behind the panel in the bed of the dump truck. There was radio communication between the experimental vehicle and the test truck. Participants were stationed inside a 2002 Cadillac Escalade, along with an in-vehicle experimenter who provided directions and recorded responses on a laptop computer.

Lights

The lights used for this experiment were commercially available light sources acquired from manufacturers. The light sources were selected for the ease of use, photometric characteristics, and suitability for the experiment (available in the required colors, with various intensities and flash patterns also available). The retroreflective tape used in this experiment was Avery Dennison DOT Type C2 material. The retroreflective tape was placed underneath the LED and strobe lights, and was covered with a magnetically fastened black strip of rubber when it was not being tested.

Methods

Subjects were greeted and asked to show their driver's licenses. The purpose of the study was explained and they then read and signed the informed consent form. Three vision tests were administered: the Snellen vision test, contrast sensitivity test, and color blindness test. Subjects had to have a minimum of 20/40 vision using the Snellen acuity test in order to participate. Prior to the test trials, time was taken to orient subjects to the study, the vehicle, and the procedures. Subjects were shown how to adjust the position of the seat in order to be comfortable.

Instructions were provided once subjects were seated in the vehicle. During the daytime session, subjects were instructed to rate the conspicuity of the warning lights. Subjects then performed a maximum peripheral detection task to assess the largest angle at which they could detect the warning lights using their peripheral vision. During the nighttime session, subjects again rated the conspicuity of the warning lights. Subjects were next asked to identify what function a vehicle might be performing with the viewed warning-light pattern. Once all 41 nighttime conditions were seen and rated, the vehicle was moved closer to the truck containing the lighting panel, and participants were asked to rate each condition according to a discomfort glare scale.

It should be noted that attention-getting ratings were taken 400 ft away from the lights during both daytime and nighttime sessions, while the glare ratings were taken at 150 ft from the lighting panel during the nighttime sessions. The test truck was positioned at the top of a hill during the daytime session to support the "daylighting" tests and at the bottom of the hill during the nighttime session to maximize the dark background and to minimize distraction to passing vehicles. Figure 3 shows the physical arrangement of the test vehicles for the daytime and nighttime sessions.

Half of the participants completed sessions that used LED panel-mounted lights, while the other half viewed halogen panel-mounted lights. The division was necessary owing to limited time and resources. Upon completion of testing, subjects were asked to provide comments on the warning lights, and then were paid at a rate of $20/h.

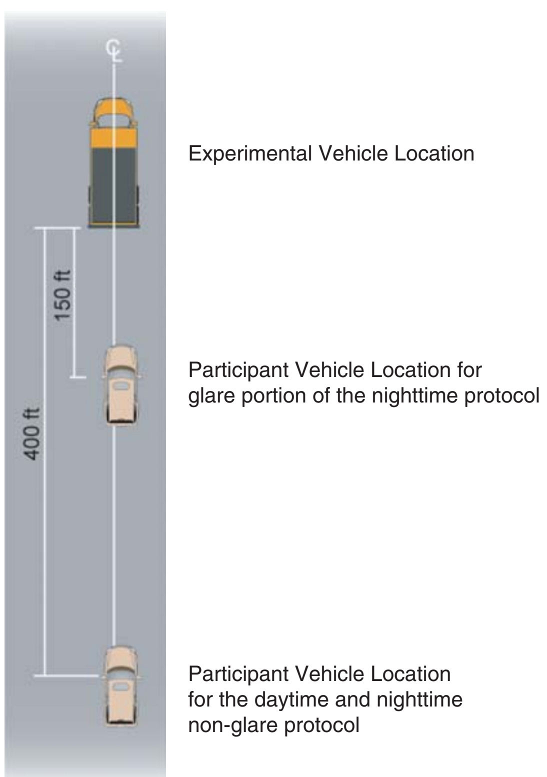

Figure 3. Testing area layout for nighttime and daytime testing.

Data Analysis

The data analysis was undertaken in four parts: analysis of the halogen, LED and strobe panel lights; analysis of the rotating beacons; analysis of passive retroreflectivity; and analysis of the position of the beacons with respect to the daylight.

The four dependent (measured) variables of daytime attention-getting, daytime peripheral detection angle, nighttime attention-getting, and nighttime glare were considered in each of these analyses; the other variable, recognition scale, was considered separately. For the lamp type factor, the halogen, LED, and strobe sources could not be directly compared because the halogen and LED were each presented to only half of the participants; lamp types were compared in pairs: halogen and LED, strobe and halogen, and LED and strobe.

Summary of Results

Lamp Type, Intensity, and Color Comparisons

The first factors considered in these analyses were lamp type, intensity, and light color. The results are summarized below, with only the significant findings discussed:

- **Peripheral Detection Angle**
  - Overall, the amber and the white light sources typically performed equivalently for detection with peripheral vision; the red and the blue performed worse.
  - The paired comparisons that included a strobe (i.e., strobe/halogen and strobe/LED comparisons) performed better than the halogen/LED comparison.
  - The lamp-type-by-color interaction was significant for the halogen and LED comparison. The halogen light sources performed significantly worse than the LEDs for all colors except white (in which halogen and LED performed virtually identically). In this comparison, the red LED was also the best performer for peripheral detection angle, which is different than what was found in all other relationships, where amber and white performed better. The purity of the red LED source may have resulted in a stronger response than for the red halogen source.
- **Attention-Getting Rating**
  - There was a statistically significant intensity difference for both the daytime and nighttime attention-getting rating for the halogen and strobe comparison. This difference showed that a higher effective intensity results in a significantly higher attention-getting rating.
  - There was a significant lamp-type-by-color interaction in the daytime, with strobes having a higher attention-getting rating in all colors except for the red LED. This result could be due to two factors: the LED configuration was a steady light source as opposed to a flashing strobe,

and the red LED configuration may thus have appeared to be similar to vehicle brake lights.
   - The nighttime attention-getting rating of the light sources was higher than the daytime rating for the same lights.
- **Discomfort Glare Rating**
   - Like the attention-getting scale, only intensity was significant for the halogen and strobe comparison, with a higher effective intensity producing a higher glare rating.
   - It was also noted that a higher attention-getting rating also corresponds to a higher glare rating (in other words, it is difficult to find a light source that is more attention-getting without also having higher glare).
- **Summary**
   - Through all of these comparisons of the halogen and LED sources, only peripheral detection angle showed a difference between these two light sources. In this case, the color was the most significant, with the amber and the white light sources performing better than the blue and red.
   - For attention-getting and glare, the most critical aspect of these comparisons is the effective intensity of the light source. However, these results must be balanced because a higher effective intensity provides a higher attention-getting rating, but also causes a higher glare rating.
   - One aspect that is worth noting is that the LED and halogen comparisons to the strobe compared the *steady* halogen or LED systems to the *flashing* strobe systems. This aspect is an artifact of the research design. However, the strobe and the flash characteristics were investigated in two other comparisons.

Flash Characteristics

Other comparisons investigated the impact of the flashing pattern on the measured results. For this analysis, only the amber panel lighting configurations were used to investigate each of the dependent variables. There were no significant findings for the daytime versus nighttime attention-getting ratings.

- **Peripheral Detection Angle**
   - There was a significant four-way interaction for ability to detect the flash patterns in the peripheral vision. This interaction is difficult to interpret because of its complexity. In general, a lower effective intensity resulted in a worse detection angle; the LED source performed better than the halogen source for older drivers, but was not significantly better for younger drivers; the steady condition had worse results than the flashing conditions; the higher frequency flashing seems to be just slightly worse than the lower frequency condition; and the synchronous flash was slightly better than the asynchronous.
   - Other comparisons indicate that the flashing behavior of the lights and the number of sources are more important than the effective intensity of the sources, with flashing being better than steady. The asynchronous pattern also seems to provide an additional benefit over the synchronous condition.
- **Attention-Getting Rating**
   - The daytime attention-getting rating results showed that the flash patterns have a higher attention-getting rating than the steady condition. However, there seems to be very little difference between the flash patterns and frequencies.
   - Higher intensities resulted in a higher attention-getting rating, regardless of flash pattern.
- **Glare Rating**
   - The steady condition had a higher glare rating, indicating that a greater amount of glare was experienced by the observer. However, as seen in the previous comparison, it was also the worst condition for attention-getting. Therefore, it seems that the flashing light provides a way of getting attention without causing a higher glare experience for the observer.
   - The characteristics of the flash pattern seem to be relatively unimportant as there was no statistical difference among the asynchronous and synchronous flash patterns.

Strobe Lights

For the strobe lamps, two analyses were conducted. One analysis compared the results with different flash patterns (double versus quad flash) and intensities. The other analysis concerned the color and the intensity of the strobe lamps, for which only the strobe panel lighting configurations were used.

- **Flash Patterns and Intensity**
   - Only the amber lamps were used in this analysis. None of the four dependent variables (daytime attention-getting rating, nighttime attention-getting rating, peripheral detection angle, and glare rating) showed significant results for flash pattern or intensity. This outcome suggests that the dual-flash versus quad-flash characteristics of the light source are not significant considerations in the requirements for lighting.
- **Color and Intensity**
   - Only the dual flash patterns were used in this analysis. The results for the four dependent variables (daytime attention-getting rating, nighttime attention-getting rating, peripheral detection angle, and glare rating) showed that the color is significant for peripheral detection, as well as for glare, and that intensity is significant for daytime attention-getting.

- For peripheral detection, both amber and white lighting provided better performance than either red or blue.
- For glare, amber and white lighting had a greater glare rating than the red and blue systems.
- For daytime attention-getting, a higher effective intensity results in a higher attention-getting rating.

Rotating Beacons

Two analyses were performed with the rotating beacons. One analysis concerned the speed and effective intensity of the rotating beacon, and the other analysis concerned the speed and the color of the beacons, for which only the rotating beacon configurations were used.

- **Speed and Intensity**
  - Only the amber color results were used for this analysis. Neither speed nor intensity was significant for any of the four dependent variables (daytime attention-getting rating, nighttime attention-getting rating, peripheral detection angle, and glare rating). This outcome suggests that the effective intensity and speed of rotating beacons do not influence the human response to them.
- **Speed and Color**
  - These results show that color is significant for peripheral detection, and amber and white lighting exhibit better performance than red and blue lighting.
  - Analyses also showed that the speed was significant for peripheral detection. In this case, the slower beacon provides a larger (better) peripheral detection angle than the faster beacon. This outcome is likely related to the duration of the flash.

Passive

In this analysis, the passive treatment (retroreflective tape) was compared to the panel lighting condition. For this comparison, the low-intensity steady condition for each color was compared to the passive tape condition.

- **Peripheral Detection Angle**
  - The performance of the retroreflective tape was significantly lower than that of the other conditions for peripheral detection. This outcome was to be expected because retroreflective tape relies on the headlamps of an approaching vehicle for its luminance, and the Peripheral Detection test was a daytime evaluation of the lighting conditions.
- **Attention-Getting Rating**
  - As with all of the lighting conditions tested, the nighttime condition showed a higher rating than the daytime condition. The passive condition was significantly increased during the nighttime, but did not rise to the level of the lighted conditions.
- **Glare**
  - As expected, the glare from the retroreflective tape was minimal as compared to the light sources.
- **Summary**
  - The results of the passive condition showed that there must be internally illuminated sources in order to maximize the attention-getting and the peripheral detection factors. These sources will increase the glare experienced by the observer but the resulting increase in conspicuity is likely justified.
  - The passive tape provided an additional impact during the nighttime condition and can be a suitable supplement to provide an additional source of nighttime visibility. However, it should not be relied upon as a sole source of warning information.

Beacon Type and Position

One of the issues with a beacon-type source is the daylight infringement behind the light. As mentioned, this issue was tested by placing a series of beacons either on the top of the test platform or on a shelf with the test platform behind the light source. The results of this test were analyzed using lamp type and location. For this analysis, the sources were all in beacon format and were all amber in color.

- **Attention-Getting Rating**
  - The daytime attention-getting rating was lower than the nighttime, which is consistent with previous results.
  - In terms of lamp type, the LED and rotator sources did not differ in attention-getting, but the strobe performed worse than either of them. It is likely that these results are related to the light characteristics of the sources. The rotating beacons provided a higher intensity over time than the strobes and the LEDs. Similarly, the LEDs provided higher color purity than the other two sources.
- **Peripheral Detection Angle**
  - The lower shelf location provided a higher performance than the location on the top of the test panel. The location result shows that less light is lost to the sky when there is a backing behind the light. It should be noted that the test panel in this configuration was black and that a different background color may change the impact of the location.
  - For lamp type, rotating beacons provided the best performance and the strobe and the LED provided the worse but similar performance. The rotating beacon performance is likely related to the higher time-averaged intensity provided by this configuration.
- **Glare**
  - The rotating beacon and the LED beacon performed equivalently, while the strobe had a lower glare rating—

a similar grouping to that found with the attention-getting rating. As indicated before, the higher attention-getting sources also have a higher glare rating.

- **Summary**
  - The results of this test show that having the beacon appear against a background is important to the detectability of the source. The background provides a consistent contrast for the light source and therefore higher and predictable performance. However, this option must be traded off against the alternative of having more beacons so that they can be seen from the front of the vehicle as well as the back.

Vehicle Recognition Results

The vehicle recognition questionnaire was used to identify any lighting patterns that might resemble a standard pattern not used for the maintenance vehicles that were part of this investigation. In other words, what lighting patterns had some sort of intrinsic meaning for the viewer, such as "This must be a law enforcement vehicle"?

- **Color**
  - Blue was predominantly recognized as law enforcement. This observation was to be expected as blue is the lighting color used on law enforcement vehicles in the Commonwealth of Virginia.
  - Amber and white were predominantly associated with maintenance and construction, including towing.
  - Red was associated with medical and fire response.
- **Overall Lighting Aspects**
  - The second aspect of the vehicle recognition questionnaire was the identification of which of the lighting aspects are important to the identification. Color was the predominant response, followed by flash cycle. The light position was not considered to be important by participants; however, the lighting configurations were predominantly in the same location throughout the investigation. Effective intensity also did not seem to be important in the vehicle recognition.

Photometric Comparison

Comparing the results of the photometric testing with that of the static testing provides some insight into the required limits for lighting on maintenance vehicles. The Form Factor method was shown to be the best method of photometric testing for effective intensity for the purpose of this study. Each of the individual static testing metrics was compared to the Form Factor results of the light sources. These comparisons were only made for the panel lights.

- **Attention-Getting Ratings**
  - There was a positive correlation between daytime attention-getting and effective intensity for all colors and lamp types. Amber lights were typically rated higher regardless of effective intensity, with halogen amber lights being rated the best. It appears that the relationship of the rating to the effective intensity of the light source is a linear–log relationship, suggesting that the gains in attention-getting diminish with brighter light sources. This relationship is typical for most human responses to light sources.
  - There was also a positive correlation between nighttime attention-getting rating and effective intensity that is similar to, but smaller than, that between daytime attention-getting rating and effective intensity. Ratings of low-effective-intensity lights were much higher at night because of the high contrast of the lights and their background. Ratings of relatively high-effective-intensity lights did not increase as much, likely because of ceiling effects of the rating scale. In this scenario, the blue LEDs performed well for conspicuity even though they were among the least intense. The ratings of the white LEDs also increased dramatically during nighttime trials. The ratings of the amber halogens, which were among the best in the daytime, remained relatively unchanged at nighttime.
- **Peripheral Detection Angle**
  - Strobes performed much better for the peripheral detection angle than other lights with similar effective intensity, likely because of the strobes' relatively fast flashing patterns.
  - Amber strobes provided the best performance, better than the amber LEDs that were more than twice as intense. The linear–log relationship of the peripheral detection angle to the photometric effective intensity was more dramatic in this comparison.
- **Discomfort Glare**
  - Blue LEDs and white LEDs performed poorly on the discomfort glare scale, even though they had low effective intensity. The same linear–log relationship exists in this comparison.
- **Photometric Limits**
  - The photometric levels required for the warning lights on the vehicles can be established based on the relationship of the rating scales to the photometric measurements. The glare rating would serve as the upper limit of the specification for the effective intensity because the relationship shows that the higher the effective intensity, the greater the glare. The attention-getting rating would then be used as the minimum level because it is a target that must be surpassed to provide adequate conspicuity of the light sources.

Different analyses were conducted for daytime and nighttime; because glare is not evident during the day, it does not provide an upper limit to the photometric rating of the light source. Therefore, a dual level of light source should be considered. A nighttime range and a daytime range of light intensities should be considered to provide adequate attention-getting while still limiting glare. Proposed values based on a discomfort glare level of 6 and an attention-getting rating of 5 for both the daytime and nighttime were developed and are presented in the guidelines (see the attachment).

Discussion

The results from this static experiment were specifically analyzed to enable the development of guidelines for the application of warning lights to maintenance vehicles. These results support specific recommendations relevant to the lighting design. The possible areas of consideration are lamp color, effective intensity, flash pattern, lamp type, retroreflective tape use, and lamp location:

- **Color.** The results indicate that amber and white are the lighting colors that should be considered for maintenance vehicles. These colors provided the highest conspicuity in the peripheral detection task and the best attention-getting ratings and were most closely linked to maintenance vehicles and construction activities in the participants' minds.
- **Effective Intensity.** The effective intensity of the light source needs to be balanced between the higher conspicuity provided by a higher effective intensity and the experience of glare by the driver. The results show that a higher effective intensity of light source provides a greater conspicuity both during daytime and nighttime. However, the higher effective intensity of the light source leads to a higher glare experience by the approaching observer.
- **Flash Pattern.** The results show that the use of a flashing light provides both high conspicuity and reduced glare. In particular, the use of an asynchronous flashing light seemed to provide an increased benefit over the synchronous pattern. The frequency of the flashing seemed to have a minimal impact on the response (a lower frequency seemed to provide only a slightly higher response).
- **Light Type.** The use of halogen or LED sources seemed to not be significant in the analyses. However, in some limited applications, the LED seemed to provide a higher response, likely due to the color purity for this type of light.
- **Retroreflective Tape.** The results indicate that the retroreflective tape is not suitable as the only marking option on maintenance vehicles; however, this tape seemed to provide an additional benefit at night, with regard to attention-getting.
- **Lamp Location.** There was an improved benefit during the daytime to have the light source appear against a black background by providing a contrast that can be controlled by the agency operating the vehicle. Having the lamp appear against a non-black background may not be as effective.

Preparation for Dynamic Performance Testing

To more fully explore the requirements found in the static screening experiment, the performance experiment was undertaken with four lighting arrangements. These were rotating beacons in two different locations and panels lights in both LED and strobe configurations.

CHAPTER 4

Performance Experiment

From the results of the static screening experiment, four warning-light configurations were selected for further testing in dynamic conditions. Three measures considered the nighttime identifiability of a maintenance vehicle with warning lights; the detectability of a pedestrian standing close to the maintenance vehicle; and the ranking of the vehicle lighting in terms of discomfort glare, attention-getting, and urgency. The study included an uninformed trial where participants viewed the lighting systems without knowing the nature of the study and also incorporated adverse weather in the testing conditions.

Experimental Methods

Experimental Design

The choice of independent variables was driven by the results of the static screening experiment, and the need to provide realistic test scenarios that drivers are likely to encounter in everyday driving. The experiment included between-subjects variables (gender and age, each with two levels) and within-subject variables (warning light and pedestrian, each with four levels; glare and ambient lighting, each with two levels; and weather with three levels). Because of the large number of variables, a mixed-factor partial factorial design was used to allow exploration of the most relevant main effects and interactions. The final experiment design resulted in a total of 116 conditions for each participant: 40 during the day, and 76 during the night.

Within-Subject Variables

Warning Light. Four warning light configurations were used: high-mounted rotating beacon, low-mounted rotating beacon, LED, and strobe.

Pedestrian. The pedestrian was presented at two different distances from the experimental truck to see how each light affected the visibility of the pedestrian. A pedestrian was also presented at the same distances without the truck as a baseline measurement for pedestrian detection.

Glare. The glare independent variable provided insight into the ability of the warning-light system to be visible when other (and particularly opposing) vehicles are present. The glare was simulated using the headlights of a parked vehicle close to the experimental truck.

Weather. The weather independent variable provided insight on which type of warning light performs best in realistic weather conditions. The three levels were dry, rain, and fog. Rain and fog were kept consistent among participants by using a weather-making system to control the levels.

Ambient Lighting. The ambient lighting independent variable provided insight on which type of warning light performs best in daytime and nighttime conditions.

Assignment of Treatments

Treatments were balanced across age and gender to eliminate presentation bias among the groups. A balanced Latin Square was used to create the orders of presentation for each driving session. Eight orders were used for nighttime sessions, with each participant within an age and gender group receiving a different order. Four orders were used for daytime sessions, with two participants within an age and gender group receiving the same condition.

Dependent Variables

Seven dependent variables were used in this investigation. The dependent variable of lane-change distance was tested only during the uninformed trial, which was at night in clear weather. The dependent variables of vehicle identification distance, pedestrian detection distance, and discomfort glare rating were tested only during nighttime conditions (night dry, night rain, and night fog). The dependent variables of attention-getting rating and confidence rating were tested only during daytime conditions (day dry and day fog). The dependent variable of urgency rating was tested during all nighttime conditions and during daytime fog conditions.

Lane-Change Distance. During the uninformed trial, participants were forced to pass the slow-moving dump truck (experimental vehicle), unaware that the truck was involved in the study. The distance at which the participant initiated the lane change to pass the truck was marked as the lane-change distance.

Vehicle Identification Distance. To establish each warning light's ability to alert a driver to the presence of a maintenance vehicle, the distance at which a participant could identify the light source as belonging to a vehicle was recorded. The distance traveled between this point and when the participant vehicle passed the experimental truck was defined as the vehicle identification distance for the warning light on display. This measurement was taken during each nighttime condition.

Pedestrian Detection Distance. To establish each warning light's ability to allow a driver to see maintenance workers near a maintenance vehicle, the distance at which a participant could detect a pedestrian standing near the experimental dump truck was recorded. The pedestrian detection distance for the warning light on display was defined as the distance traveled from this point to the point at which the participant vehicle passed the pedestrian. This measurement, along with a baseline measurement, was taken during each nighttime condition.

Urgency. The urgency rating dependent variable measured the level of urgency that subjects felt was conveyed by the warning lights. A five-point Likert-type rating scale with end points "not at all urgent" and "totally urgent" was used to capture their ratings. This scale was administered during each nighttime condition and the daytime fog condition.

Discomfort Glare. The discomfort glare rating dependent variable measured the discomfort experienced by the subjects when presented with the warning lights. A nine-point rating scale with end points "not noticeable" and "unbearable" was used to capture their ratings. This scale was administered only at nighttime when discomfort glare is at its worst due to the high degree of contrast between the lights and their backgrounds.

Confidence. The confidence rating dependent variable measured the confidence level of the subjects that they could see the warning light. The scale was a five-point Likert-type rating scale with end points "not at all confident" and "totally confident." This scale was administered only during daytime conditions when there was a low degree of contrast between the lights and the background.

Attention-Getting. To establish the effectiveness of the warning lights, a metric for conspicuity was established. This was done using a seven-point rating scale ranging from "not at all attention getting" to "extremely attention getting." This scale was administered during daytime conditions.

Participants

Thirty-two subjects, 16 males and 16 females, were selected to participate in this study. The subjects were evenly selected from two age groups of 25 to 35 years of age and 65+ years of age. IRB approval was obtained prior to recruiting subjects. When subjects arrived for the first session, they signed an informed consent form before beginning any experimental activities. Subjects were paid $20/h for each driving session, and a $30 bonus if they completed all four driving sessions. They were allowed to withdraw at any point in time, with compensation adjusted accordingly.

Apparatus

Test Road

The experiment took place on the Smart Road—a 2.2-mile-long controlled-access, two-lane road. A 0.5-mile section of the Smart Road is equipped with an artificial weather-making system that was used to create the rain and fog conditions for this study. A degree of control was attained by not allowing public vehicles and pedestrians to enter the Smart Road and by controlling the level of the rain and fog so that it was consistent among participants.

Test Vehicles

Like the static experiment, two test vehicles were used in this experiment: a participant vehicle and an experimental vehicle. The experimental vehicle was the same VDOT dump truck that was used in the static experiment. However, the dump truck was outfitted with the four warning lights of interest (Figure 4).

The high beacon lights were placed above the cab of the truck, one on each side. The low beacons were placed on small shelves on the back of the tailgate, one on each side. The strobes and LEDs were mounted on a rack on the tailgate, one on each side.

All lights were manually controlled by an operator who sat in the cab of the truck. There was radio communication between the participant vehicle and the experimental vehicle

Figure 4. VDOT dump truck outfitted with warning lights.

that allowed the in-vehicle experimenter to prompt the light operator for the next light. The participants drove a 2002 Cadillac Escalade; an in-vehicle experimenter rode along to provide directions and to record data. Vehicle identification distance and pedestrian detection distance were recorded using a data acquisition system (DAS) installed in the vehicle. Attention-getting, discomfort glare, urgency, and confidence ratings were recorded by hand on an order sheet and later entered into a spreadsheet.

The DAS recorded vehicle network data such as acceleration and speed, as well as four camera angles and information entered by the in-vehicle experimenter such as the participant number, participant age, experimental order, and button presses.

Pedestrian

The pedestrian was an on-road experimenter who wore denim surgical scrubs and a VDOT-issued reflective safety vest. Depending on the presentation order, the pedestrian would either stand 40 ft or 80 ft behind the dump truck in the center of the lane for each lap driven by the participant. When the participants verbally indicated that they could see the pedestrian, the in-vehicle experimenter would say "clear" over the radio. This was the pedestrian's signal to clear the road. If for any reason the in-vehicle experimenter did not give the clear signal, the pedestrian would clear the roadway automatically when the vehicle reached a predetermined proximity. Once the participant vehicle turned around and passed the dump truck on the way back to the top of the road, the pedestrian would get into position for the next lap.

A baseline pedestrian was also presented several times for each participant. This pedestrian would follow the same procedures, but stood on a section of road away from the dump truck. This allowed for a comparison of detection distances.

Stimuli

The stimuli used for this experiment were commercially available light sources acquired from manufacturers. The light sources were selected based on their performance in the static screening experiment, photometric characteristics, and the suitability for the experiment.

High-Mounted Beacon. The high-mounted beacon used was a PSE Amber, model 550 FRAMH 12 V 100 W. A summary of the rotating beacon light characteristics is provided in Appendix C1.

Low-Mounted Beacon. The low-mounted beacon used was also a PSE Amber, model 550 FRAMH 12 V 100 W, also provided in Appendix C1.

LED. The LED used was an amber Whelen 500 Linear LED Flash Light. One light on each side of the truck was used. The LEDs were displayed in a 1 Hz asynchronous pattern. A summary of the LED light characteristics is provided in Appendix C1.

Strobe. The strobe used was an amber Whelen 500 Linear Strobe Light. One strobe light on each side of the truck was used. The strobes were displayed in a 1 Hz asynchronous pattern. A summary of the strobe light characteristics is provided in Appendix C1.

Methods

Upon arriving at VTTI for the first driving session, each participant was asked to read and sign the Information Sheet (Appendix E1), and fill out a health and vision screening questionnaire. Each participant was also required to take an informal visual acuity test using a Snellen chart. The vision test was performed to ensure that all participants had at least 20/40 vision, which is the legal minimum to hold a driver's license in Virginia. Participants were tested for color blindness using pseudo isochromatic plates, but were not excluded based on results.

At the beginning of each driving session, the participants were given an information sheet that explained that they would be expected to drive on Main Street in Blacksburg and on the Smart Road under various weather conditions. It also outlined the risks involved, and their rights and responsibilities as participants. Before the participants' first driving session, they would sign and date the information sheet. Upon arriving at VTTI for each subsequent driving session, the participants were asked to review the same sheet, and initial and date it for each visit.

First Driving Session: Surprise, Nighttime Dry, and Nighttime Rain

The first driving session consisted of three parts: the surprise, nighttime dry, and nighttime rain trials. During the surprise trial, the participant was unaware that the focus of the study was on vehicle warning lights. Participants were instructed to drive on Main Street towards Blacksburg, where the experimental dump truck was waiting ahead. Instructions read to the participant were designed to force them into passing the truck. The lane-change distance was defined as the distance between the participant vehicle and the truck at the moment a lane change was initiated. This trial was followed up by a questionnaire, which was administered in the nearest parking lot. The participant was then debriefed on the true purpose of the research and signed an informed consent form for continued participation.

During the nighttime dry trials, the participant drove on the Smart Road toward the experimental dump truck that was displaying one of the four warning lights. The participant would verbally indicate when he or she could identify the light source as a vehicle, and when he or she could detect a pedestrian in the roadway near the truck. These points were marked by the in-vehicle experimenter in the DAS data by use of a push button. The distance between the participant vehicle and the identified target (i.e., the dump truck or pedestrian) was defined as the vehicle identification and pedestrian detection distances for the warning light on display. This procedure was repeated twice for each warning light: one trial with a glare vehicle present and one without. A second pedestrian was occasionally presented on a section of road not near the truck in order to get a baseline pedestrian detection distance.

In addition, participants were also asked to rate the warning lights in terms of discomfort glare and urgency at two distances (2400 ft and 1200 ft). This procedure was also done twice: once with a glare vehicle and once without. The first ratings were done after the first four laps, and the second ratings were done after the last four laps. Depending on the presentation order being used, a glare vehicle would either be present for the first two ratings or for the last two ratings.

The rain towers were then turned on, and the same steps were repeated for the nighttime rain condition. The participant's speed limit was reduced from 35 mph to 25 mph for safety because of the wet road surface and decreased visibility of the pedestrian. The distances at which the discomfort glare and urgency ratings were recorded were also reduced (to 1200 ft and 600 ft). Once all laps and ratings were complete, participants were instructed to return to the VTTI building where they were compensated for their participation.

Second Driving Session: Daytime Dry

During the daytime sessions, only subjective ratings of the warning lights were collected. Ratings were taken at four distances (4800 ft, 3600 ft, 2400 ft, and 1200 ft) and in two directions (facing downhill and facing uphill). These directions were used because of the difference in contrast of the lights and their background. With the uphill view of the experimental truck, the warning lights on top of the vehicle were visible against the sky, whereas for the downhill view, the lights appeared against a foliage background as shown in Figure 5.

For this session, the participants were first asked if they could see the warning light being displayed. If they answered "yes," they were asked to rate how confident they were that they saw it using the confidence rating scale. Finally, the participants were asked to rate the attention-getting nature of the light using the attention-getting rating scale. The participants would answer these questions about each warning light at each distance. The downhill ratings were collected first, followed by the uphill ratings. Upon completion, the participants were instructed to return to the building where they were paid for their time.

Third Driving Session: Nighttime Fog

During the nighttime fog session, the participants followed the same protocol as the nighttime rain session. For safety, the participants were instructed to drive at 15 mph while in the fog. Each participant drove a total of eight laps on the Smart Road, indicating when they could identify the light source as a vehicle and when they could detect the pedestrians in the road. After the fourth and eighth laps, the participants were

Lights against foliage in downhill view

Lights against sky in uphill view.

Figure 5. Views of the experimental truck.

asked to rate the discomfort glare and urgency for each warning light at 600 ft and 300 ft. When the last set of ratings was complete, the participants were instructed to drive back to the building where they were paid for their participation.

Fourth Driving Session: Daytime Fog

During the fourth driving session, participants viewed each warning light at 600 ft and 300 ft. At each distance, subjects were first asked if they could see each warning light. If they answered "yes," they were also asked how confident they were that they saw the light using the confidence rating scale, to rate the attention-getting nature of the light using the attention-getting rating scale, and to rate the urgency of the light. These questions were asked for each light and catch trial (no light presented). Once both sets of ratings were done, the participants were instructed to drive back to the building where they were paid for their participation. Subjects who participated in all four driving sessions also received a $30 bonus.

Data Analysis

A statistical analysis was undertaken that compared the results using analysis of variance (ANOVA) testing for each of the independent and dependent variables. Factors and interactions were considered to be significant at an $\alpha = 95\%$ level. When possible, a Student-Newman-Keuls (SNK) pairwise post hoc test was used to further determine significant factors.

The final step was the photometric analysis of the light sources based on the measurements from the earlier experiment. Trends and the correlation of the photometry and the dynamic testing were compared to provide further insight into the lighting system performance.

Summary of Results

The results of the dynamic conditions—lane-change, vehicle identification, and pedestrian detection distances—will be discussed first. These results are then followed by the analysis of the rankings of attention-getting, confidence, urgency, and glare.

Dynamic Conditions

- **Lane Change Distance**
  - The LED warning lights caused significantly longer lane-change distances than either the beacons (low- and high-mounted) or the strobes. This result may be related to the light's effective intensity that caused participants to change lanes to avoid glare from the lights.
  - Results from all other warning lights were not significantly different from each other.
- **Vehicle Identification Distance**
  - Vehicle identification distances were significantly shorter (worse) in rain and fog conditions than in dry conditions (Figure 6).
  - High-mounted beacons provided significantly longer (better) identification distances than the other warning lights (Figure 7). The light's separation from the vehicle's tail lights may have been a contributing factor because

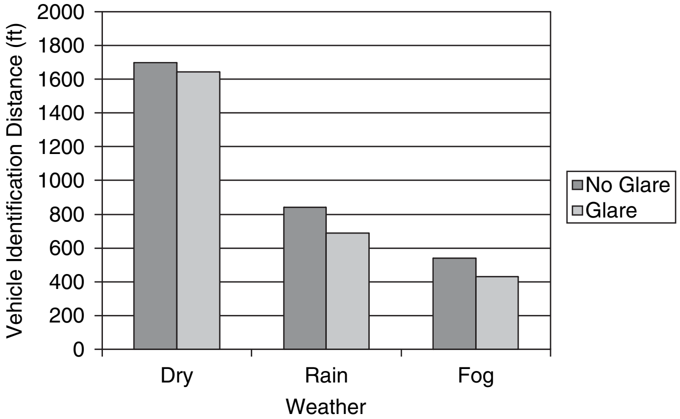

Figure 6. Mean vehicle identification distance for each glare and weather condition.

a majority of participants suggested that the tail lights were the main influence in determining that the light source was located on a vehicle.
- LEDs provided significantly shorter identification distances than the other warning lights (Figure 7). This phenomenon may be attributed to the lights washing out the vehicle's tail lights because of their proximity and high intensity.

- **Pedestrian Detection Distance**
  - Pairwise post hoc SNK analysis found that detection distances were significantly shorter in rain and fog conditions than in dry conditions (Figure 8).
  - A pairwise SNK analysis also found that the LEDs had a significantly shorter pedestrian detection distance than all other warning lights (Figure 9). This phenomenon is likely attributed to a bloom effect caused by the light's

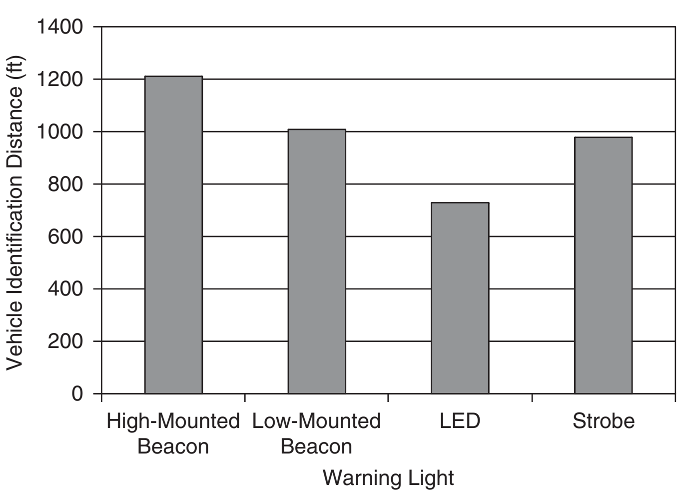

Figure 7. Mean vehicle identification distance for each warning light.

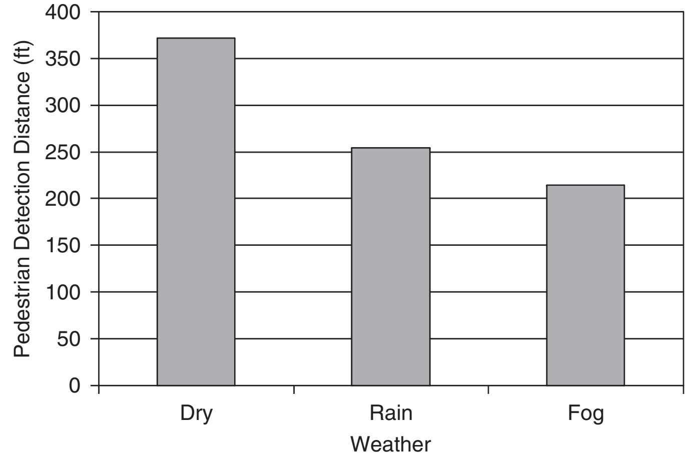

Figure 8. Mean pedestrian detection distance for each weather condition.

high effective intensity, which washed out the pedestrian's reflective vest.
  - All other warning lights produced results that were not significantly different from having no warning lights at all.

Analysis of Ratings

- **Attention-Getting Rating**
  - On average, the LEDs were rated as the most attention-getting, and the high-mounted beacons were rated the lowest. This result may be due to the relatively high effective intensity of the LEDs and the low effective intensity of the high-mounted beacons.
  - Attention-getting ratings were significantly worse for all lights except the low-mounted beacons during the uphill

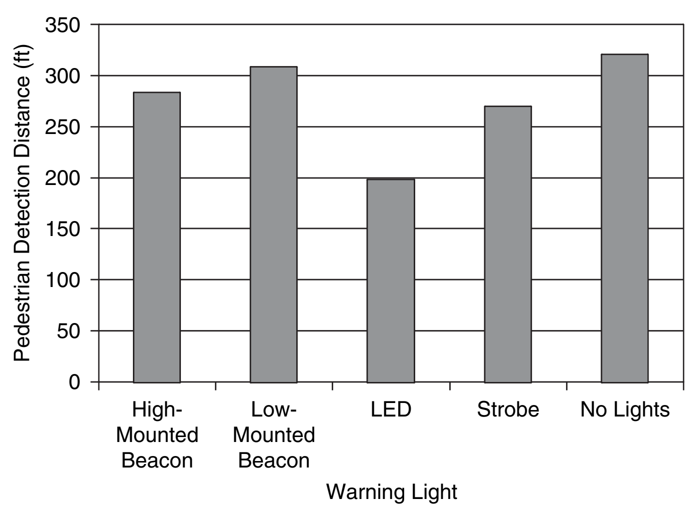

Figure 9. Mean pedestrian detection distance for each warning light.

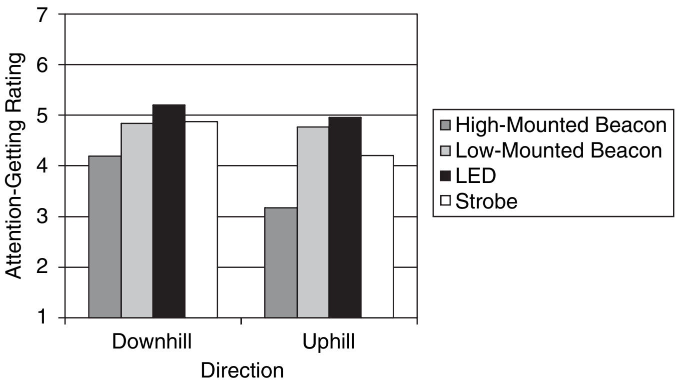

Figure 10. Mean attention-getting rating for each warning light by direction (1–7 scale).

condition (Figure 10). The high-mounted beacons were most affected by the "daylighting" effect of viewing the lights against the bright sky.

- Because the high- and low-mounted beacons are identical lights, their different attention-getting results can be attributed to their placement on the experimental truck. The high-mounted beacons become much less attention-getting during the uphill conditions because the lights blend in with the sky behind them. Because the background for the low-mounted beacons remains the same (i.e., the tailgate of the truck), there is no significant loss in attention-getting rating (Figure 11).

- **Confidence Rating**
  - Post hoc SNK analysis shows confidence rating was significantly lower for the high-mounted beacons than all other lights (Figure 12).
  - LEDs and low-mounted beacons provided the highest confidence ratings.
  - Direction had a significant impact only for the high-mounted beacons and strobes (Figure 13).

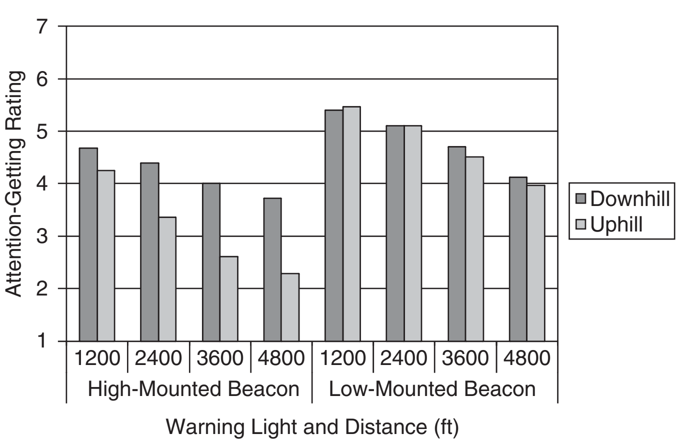

Figure 11. Mean attention-getting rating for each beacon warning light by distance and direction (1–7 scale).

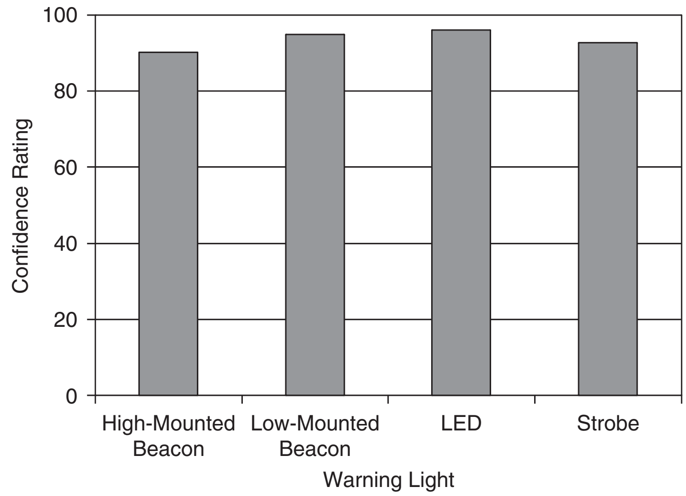

Figure 12. Mean confidence rating for each warning light (0–100 scale).

  - Increasing distance caused significant drops in confidence rating for the high-mounted beacons, worsening the effect of viewing the light against the sky.

- **Discomfort Glare**
  - For the surprise trial, average discomfort glare ratings for all warning lights were better than "satisfactory." Possible explanations are (1) the participants did not look directly at the lights because they were unaware the lights were the focus of the study, or (2) the lit roadway provided lighting on or near the roadway that made the warning lights seem less glaring by comparison.
  - On average, the LEDs had the highest discomfort glare ratings, and the high-mounted beacons had the lowest (Figure 14).
  - The LEDs were the only warning lights to get a lower discomfort glare rating in fog conditions, which may be because of increased light scatter.

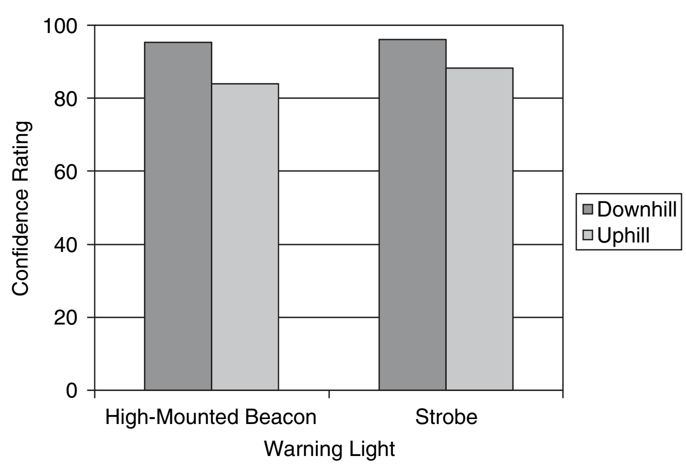

Figure 13. Mean confidence rating by direction (0–100 scale).

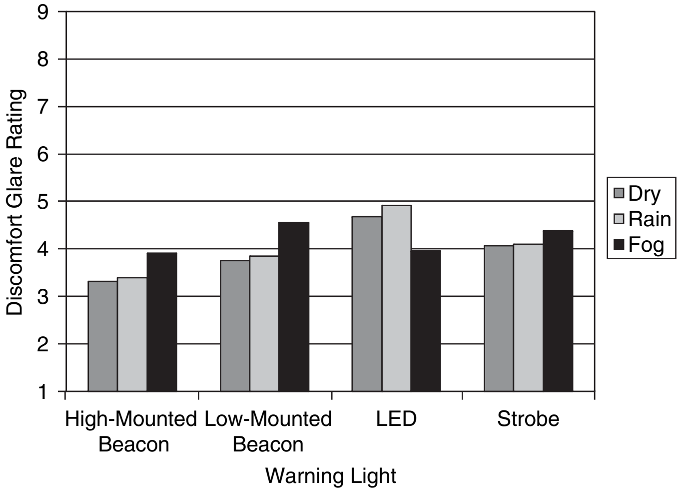

Figure 14. Mean discomfort glare rating for each warning light by weather (1–9 scale).

- All warning lights received lower discomfort glare ratings when a glare vehicle was present. This outcome may be because participants attributed more of the glare to the headlights, or because the addition of the headlights made the warning lights seem less glaring in comparison.
- Distance was a significant factor in all weather conditions, with discomfort glare ratings decreasing with increased distance.

- **Urgency**
  - For the surprise trial, the high-mounted beacons were rated significantly lower for urgency than the other warning lights. The similar low-mounted beacons had the highest average rating, possibly because the low-mounted beacons were closer to the participant's eye height and the light was reflected off the truck's tailgate making the lights seem more intense (Figure 15).
  - Post hoc analysis shows the LEDs were rated significantly lower for urgency than the other warning lights (Figure 16), possibly because of the relatively long flash duration of LEDs compared to that of the beacons and strobes.
  - A significant difference in urgency rating for the LEDs was due to age. This result may indicate that younger participants judge urgency based on flash duration, while older participants judge based on intensity.
  - Distance was a significant factor for urgency, with ratings decreasing as distance increased.

Photometric Comparison

For the photometric comparison, results of the photometric measurement for each of the lighting systems were compared to the performance of each system in terms of the dependent variables. As before, the photometric measurements used for the comparison were derived using the Form Factor method.

- **Vehicle Identification Distance**
  - For vehicle identification distance, the high- and low-mounted beacons have the same effective intensity but different performance levels. The distance of the beacons from the vehicle's tail lights, which participants used to identify the vehicle, provided the higher performance for the high-mounted beacons.
  - The LEDs had the shortest vehicle identification distance despite having the highest effective intensity. The light's long flash duration gave the appearance of a slow flash, which participants confused the most with other roadway markings such as flashing signs and construction markers.

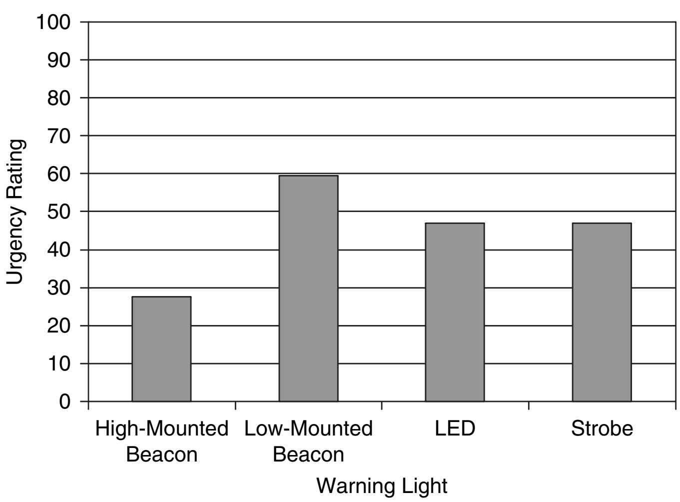

Figure 15. Mean urgency rating for each warning light following the surprise trial (0–100 scale).

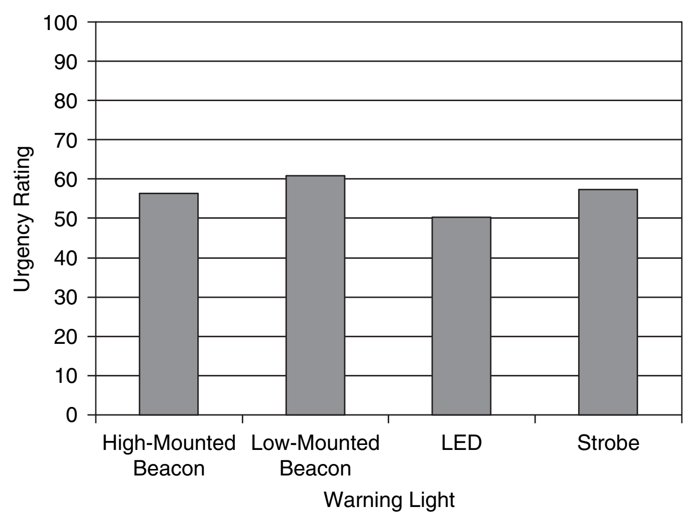

Figure 16. Mean urgency rating for each warning light (0–100 scale).

- **Pedestrian Detection Distance**
  - The LEDs also had the shortest pedestrian detection distance due to the high effective intensity of the light washing out the view of the pedestrian (Figure 17).
  - The other (non-LED) warning lights had similar performances to each other with regard to pedestrian detection distance; however, the low-mounted beacons had the highest mean distance. This result may be because the lights and the illuminated tailgate provided a contrasting background for the pedestrian's silhouette.
- **Confidence Rating**
  - The LEDs provided the highest confidence ratings due to higher effective intensity; however, from an application standpoint, the performance of every light was very high.
  - The low-mounted beacons provided higher confidence ratings than the high-mounted beacons of the same effective intensity. This result was because the high-mounted beacons were more affected by "daylighting" during the uphill conditions.
- **Attention-Getting Rating**
  - The high effective intensity of the LEDs provided the highest attention-getting ratings (Figure 18).
  - The low-mounted beacons provided higher attention-getting ratings than the high-mounted beacons (of the same effective intensity) and the strobes (which had a higher effective intensity). The added light reflection from the tailgate may have increased the low-mounted beacons' visibility over the strobes. For the high-mounted beacons, low contrast as a result of being viewed against the sky is still a significant factor in the results.
- **Discomfort Glare**
  - As expected, the LEDs (which have the highest effective intensity) resulted in the highest discomfort glare ratings (Figure 19).

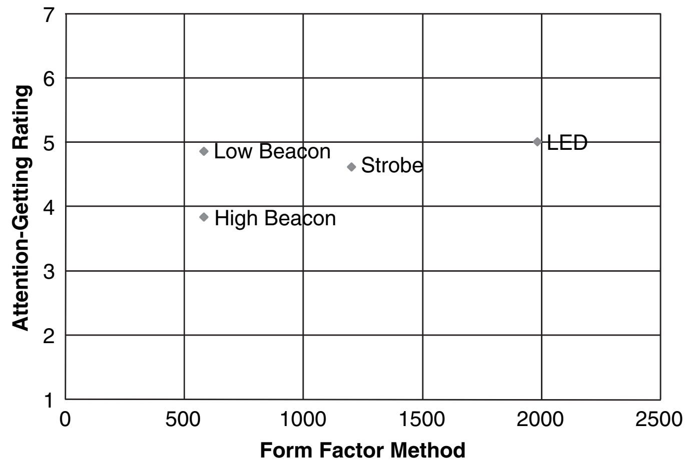

Figure 18. Daytime attention-getting rating by the light source effective intensity (1–7 scale).

  - The low-mounted beacons had a higher discomfort glare rating than the high-mounted beacons with the same effective intensity, probably because the light reflecting off the tailgate added an additional source of glare.
- **Urgency**
  - Higher effective intensity did not provide an additional urgency benefit.
  - The rotating beacons and strobes yielded a higher rating with a less intense light because the flash patterns appeared faster than the LEDs.

Discussion

The experiment has shown that many of the factors involved in the design and layout of a vehicle's warning-light system influence the response of the driver to that vehicle.

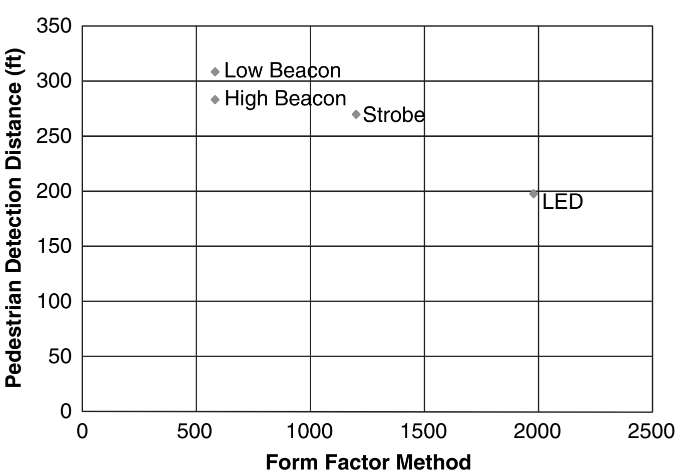

Figure 17. Pedestrian detection distance by the light source effective intensity (Form Factor method).

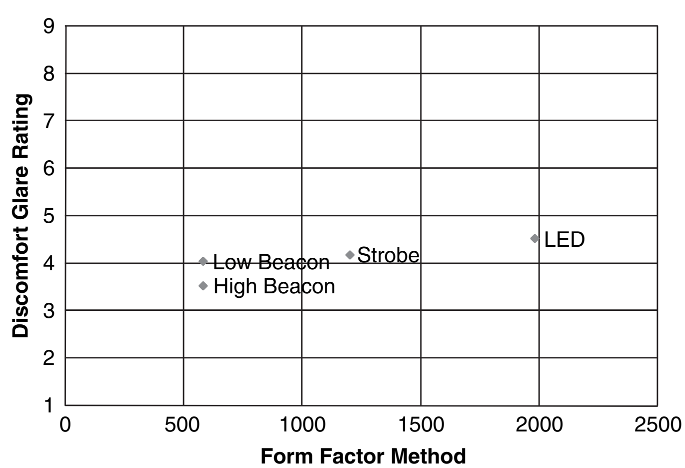

Figure 19. Discomfort glare rating by the light source effective intensity (1–9 scale).

The purpose of the dynamic experiment was to further refine the requirements of the warning-light system in a driving environment with the addition of adverse weather conditions. The aspects of the warning-light system that must be considered are the lighting layout, adverse weather influences, further refinements of the lighting characteristics, and influence of other environmental factors such as approaching vehicle glare.

- **Lighting System Layout**
  - Separation of the warning-light system from the tail lights of the vehicle aided in the identification of the vehicle. Many participants indicated that tail lights were the important cue for the vehicle identification distance.
  - One of the difficulties with placing the warning-light system high on the vehicle is that the lights may appear against the sky. The lighting should be placed either such that the vehicle is behind the source or such that a background is located behind the light in order to control the contrast.
- **Adverse Weather**
  - The influence of the rain and fog conditions did not seem to significantly influence the participants' subjective ratings of lighting system performance.
  - The rain and fog significantly reduced the vehicle identification and pedestrian detection distances for all the light sources and seemed to moderate the differences between the systems except for the LEDs.
  - The LEDs resulted in much lower pedestrian detection distances than the other systems. The LED system had the highest effective intensity, which resulted in a larger amount of light scatter observed by the approaching driver in rain and fog conditions.
  - It is expected that the effective intensity of the light would have to be limited to avoid the impact of light scatter under adverse weather.
- **Lighting Characteristics**
  - The effective intensity of the sources influenced the detection of the pedestrian and the assessment of the light source glare. The higher effective intensity reduced the ability of the driver to see the pedestrian and also resulted in a higher discomfort glare rating.
  - The vehicle detection distance was reduced for the LEDs because of the system's longer flash duration. The double flash of the strobes and the effective intensity changes of the rotating beacon seem to have provided an additional clue to the nature of the lighting system.
  - The urgency rating was also reduced for the LEDs. The urgency of the lighting system also seems to be more closely related to the apparent speed of the flashing. Use of a double flash or a beacon seems to improve the driver's response.
  - The use of a 360° light source close to the line of sight of the driver increased the experienced glare; it should be avoided.
- **Other Environmental Factors**
  - The presence of the opposing vehicle on the roadway reduced the pedestrian detection distance by increasing the disability glare.
  - The opposing vehicle also reduced the discomfort glare ratings, because the warning-light systems are not as significant a source of glare as the opposing headlamps.
  - The presence of the opposing vehicle did not affect the vehicle identification distance.
  - The presence of other lighting systems, such as the roadway lighting experienced during the surprise trial, greatly reduced the discomfort glare rating of the warning-light systems but did not change the urgency rating.
  - A higher effective-intensity light source may be required in the presence of roadway lighting, or in daylight conditions, as suggested by the lane-change distance results from the surprise trial.

CHAPTER 5

Conclusions and Suggested Research

To provide empirical evidence upon which to base guidelines for the selection and application of warning lights on maintenance vehicles, numerous light sources were examined in three experiments:

1. A *static screening experiment* in which 41 light sources were evaluated for conspicuity (attention-getting), glare, peripheral detection, and recognition. The light sources varied by color, flash pattern, flash frequency, light type, and placement on the vehicle, and were tested in varying conditions of ambient light (day vs. night) and contrast lighting.
2. A *dynamic performance experiment* in which the best three lights as determined from the static screening experiment were used in an experiment conducted on a test track. One light was used in two different positions, thus resulting in four lighting configurations. All the tested lights were amber (the color was chosen based on the results of the static screening experiment). The dynamic experiment included a surprise presentation in a visually complex environment, followed by a series of tests under controlled ambient lighting and weather conditions. The dynamic performance experiments evaluated the four lighting configurations in varying weather, distance, ambient light, and contrast lighting conditions, using measures such as pedestrian detection distance, attention-getting, and discomfort glare, among others.
3. A *photometric characterization* (stringent measurements of the light characteristics in a laboratory setting).

The results of each of the experiments were integrated into guidelines for the lighting of service vehicles.

Conclusions

Research found that several performance claims made by manufacturers of lighting systems may not reflect true measurement values. Therefore, measurement techniques for the lighting systems need to be standardized. A standard method has been developed at NIST as part of this project. The use of standardized lighting intensity measurement methods must be enforced in the lighting specifications from the state DOTs. It is recommended that the Form Factor method be specified for reporting measurement from manufacturers (although the results proved to be very similar between all of the measurement methods).

The guidelines include the technical information necessary for developing procurement specifications. The guidelines are presented in terms of the specific lights tested; however, the guidelines conclude with a section describing relevant characteristics of these lights so that purchasing decisions can be made without reference to the specific lights tested here. In other words, lights with characteristics similar to those tested here should provide similar results. The guidelines are provided as an attachment to this report.

Considerations for Future Research

- The lighting systems tested in this experiment were those generally used for maintenance vehicles, and only pairs of lights with matching characteristics were tested. Advanced lighting systems such as flashing bars and directional apparent motion systems were not tested and should be considered in future research.
- The test environment for the lighting systems used in this research was a rural road; limited testing was conducted in a semi-urban environment. The initial testing indicated that a higher effective-intensity value may be required in an environment with roadway lighting and many other vehicles. Further research may be required to establish the impact of a more urban and visually complex environment on the lighting requirements.
- This research considered one vehicle color. The integration of the lighting and the vehicle color may be sig-

nificant; alternative colors should be considered in future research.

- This research only considered rear approaches to a maintenance vehicle. Side and front approaches were not investigated, and the impact of the maintenance-vehicle headlamps could not be determined. Research addressing these factors should be considered.
- Research may be required to further investigate the relative importance of the dependent variables evaluated in this research.

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ATTACHMENT

Proposed Guidelines for the Selection and Application of Warning Lights on Roadway Operations Equipment

The proposed guidelines are the recommendations of NCHRP Project 13-02 contractor staff at Virginia Polytechnic Institute and State University. These guidelines have not been approved by NCHRP or any AASHTO committee or formally accepted for adoption by AASHTO.

Introduction

Roadway operations equipment used for construction, maintenance, utility work, and other similar activities generally operates within the roadway right-of-way. These vehicles and mobile equipment operate on all types of roadways, during daytime and nighttime hours, and under all weather conditions. To improve motorist and work-crew safety, equipment must be readily seen and recognized and, therefore, warning lights are provided on the equipment to alert motorists of potentially hazardous situations. Amber warning lights have traditionally been used, although lights of other colors are often added with the intent of helping the traveling public better see the equipment. Combinations of amber, blue, and white lights and other forms of warning lights (e.g., lighted bars, lighted "arrow sticks," strobes, light emitting diodes [LED], and alternating flashes) are used. There is a concern that this variety of lighting on roadway operations equipment has evolved without adequate consideration of the effects on the awareness and responsiveness of motorists.

These guidelines have been developed based on the results of a series of experiments that considered more than 40 lighting configurations in both static and dynamic environments. The presence of maintenance personnel, the identification of the maintenance vehicle, attention-getting, glare, peripheral detection, and urgency were all metrics in the experiments. Differing experimental conditions such as weather, the presence of other vehicles, and time of day were also considered in the experiments.

One of the primary considerations in the use of these guidelines is the purpose of the maintenance vehicle. For the purposes of these guidelines, the maintenance vehicle refers to any type of vehicle used on the roadway, whether it is being used for new construction, inspection, or general maintenance. The design of the warning-light systems may differ based on the vehicle's intended usage. For example, a snow plow will have different criteria than a small truck. The following are typical questions to be considered:

- Will the vehicle be used primarily while moving or stopped?
- Will the vehicle be used primarily in the daytime or nighttime?
- Will the vehicle be used primarily in bad weather or good weather?
- Will there be maintenance workers present around the vehicle as pedestrians?

Many vehicles are multi-purpose (i.e., they are used for many different tasks on the roadway). For example, a vehicle may be used for clearing snow in the winter and in construction and maintenance activities during the summer. The lighting system on these vehicles needs to be designed and laid out to include the considerations for all of the planned or expected vehicle uses.

Safety Issues

Safety with respect to maintenance vehicles must consider not only the maintenance vehicle and its crew but also the safety of other drivers.

Maintenance Vehicle and Crew

The safety of the maintenance-vehicle crew also has two conditions to be considered: when the maintenance crew is in the vehicle and when one or more crew members is outside of the vehicle, possibly working on the road.

For the case in which the maintenance crew is in the vehicle, the key to safety is to make the vehicle as conspicuous as possible (i.e., the maintenance vehicle and its actions and purpose are able to be perceived by other roadway users).

For the case in which the maintenance crew is outside of the vehicle, a higher effective-intensity light source was found to hinder safety by limiting the detection of a pedestrian around a vehicle. This factor will limit the overall intensity of the system. Using too many lights or lights with too high effective intensity may impede the ability of other drivers to detect a pedestrian; limiting the effective intensity of the light sources on the vehicle will mitigate this issue.

For the vehicle conspicuity, one of the requirements that was first identified in the research was the use of internally illuminated sources. Passive devices, such as retroreflective tape, did not draw the driver's attention or provide any attention-getting cues to an approaching vehicle. The warning system must provide active illumination for vehicle safety.

Flashing lights were found in the research record to be more conspicuous than continuous lights and provided a sense of urgency. An asynchronous flashing pattern (flashing side to side) also provided a higher attention-getting rating than a synchronous flash pattern (both sides flashing at once). Finally, amber light sources and white light sources also provided better responses than blue or red. Another issue with the color is the relationship of the color to the vehicle type. Amber and white were more commonly identified with maintenance vehicles, while blue and red were identified with police and fire services.

Light sources with a higher effective intensity will provide better attention-getting than a light source with a lower effective intensity. However, this was offset by the flash characteristics. A flash that provides a different flash pattern than the other lighting systems in the road environment allowed the driver to identify the vehicle sooner than a flash pattern that is similar to other lighting systems being used. Using a double flash or varying the effective intensity (such as with a rotating beacon) allowed the maintenance vehicle to be identified at a longer distance than other flash patterns. Also, when a vehicle is approached from the rear, the tail lights are primarily used for vehicle identification; locating the warning-light system high on the vehicle away from the tail lights improved vehicle identification.

Another consideration for vehicle safety was the time of day. The appearance of a lighting system against the sky limited the performance of the lighting system. For operation in daytime, it is important that the background behind the lighting system be controlled by having the light appear either against the rear of the vehicle or against a shield that provides adequate contrast and maintains the performance of the lighting system.

Other Drivers

Glare is the primary issue of a warning-light system for other drivers. Bright warning lights and oppressive flashing provide disability glare and discomfort glare for a driver of an oncoming vehicle or a vehicle passing a maintenance vehicle from behind. The warning-light system may limit the driver of another vehicle's ability to travel safely.

The glare is primarily a result of the intensity of the light source. The research showed that a high-effective-intensity light source created a greater glare response than a low-effective-intensity light source. A high-effective-intensity light source limited the ability of an approaching driver to see the pedestrian standing behind the maintenance vehicle. Glare and pedestrian detection also limit the maximum effective intensity of the warning-light system and limit the number and type of light sources placed on the maintenance vehicle.

The position of the warning-light system also impacts glare. The research showed that a light positioned close to the height of an opposing driver's line of sight created a greater glare response than a high-mounted lighting system. This response was particularly evident with 360° sources (lights that are seen from all angles), as a passing driver will be able to see that source even when they are very close to the maintenance vehicle. This consideration requires locating the light system as high on the vehicle as possible.

Lighting Issues and Considerations

Not only must the characteristics of maintenance-vehicle lighting systems be considered in terms of safety, but they also must be considered in terms of vehicle design and usage.

Vehicle Color

Vehicle color was not evaluated in this project. Nevertheless, principles of vision science indicate that a higher contrast between the vehicle color and the light color will provide better visibility. For example, if the vehicle color is white, use of white warning lights should be avoided. A black background for the light source may provide the best possible condition for lighting visibility.

Environmental Issues

The weather and the time of day for the vehicle usage must also be considered for the lighting system.

Adverse Weather

The use of the vehicle in adverse weather conditions will impact its visibility; the vehicle identification distance is diminished by adverse weather. The presence of moisture in the atmosphere will cause absorption of the light from the warning system and will cause the light to scatter. A higher effective intensity causes greater scatter and therefore a greater glare experience at night. However, higher effective intensity improves the visibility of the vehicle. The lighting effective intensity is limited by the glare in this condition, and additional lighting in adverse weather will likely cause difficulty to opposing and passing vehicles.

Ambient Light

The time of day during which the vehicle will primarily be used influences the characteristics of the lighting system. For daytime use, the lighting system must provide high conspicuity, while for nighttime use, the lighting system must provide conspicuity, while not creating excessive glare for other drivers.

A higher effective intensity of the light source must be used to provide adequate daytime conspicuity. This value may vary by the type of light source used. The research showed that halogen light at a lower effective intensity may provide higher conspicuity than LED light at a higher effective intensity. There is no evident glare in the daytime condition and therefore no maximum effective intensity limit. Another issue for the daytime condition is that of the location of the light source. The light appearing against the sky will limit the contrast of the source and will therefore limit the conspicuity of the light source. The light must appear against a controlled background for the conspicuity to remain constant.

The sources used to provide adequate daytime conspicuity will cause significant glare for opposing and passing drivers at night. At night, adequate visibility can be found at a much lower effective intensity level. The effective intensity of the lighting system must be maintained between a level that provides conspicuity and one that does not cause too much glare; the photometric effective intensity values are discussed below.

Visually Complex Environments

Research has shown that for a visually complex environment a higher effective intensity may be required to provide adequate performance as compared to a simple rural environment. Glare ratings are lower when the warning-light system is rated on a road with an overhead lighting system and opposing traffic as compared to a rural test track. Similarly, the high-effective-intensity light source causes vehicles to change lanes to pass earlier than a lower effective intensity light source does. In situations where other vehicles are present, the glare ratings are also reduced, because the warning lights are interspersed with other light sources.

In visually complex environments, a high effective intensity may be used to provide increased visibility of the vehicle while not causing too much glare for other drivers.

Lighting Selection

The lighting requirements are based on requirements for safety of the vehicle and other drivers.

Light Source Selection

There seems to be no benefit of one light source over another in general use. Because the spectral output of the source is very pure, solid-state LED sources seem to provide a benefit with some light colors. LED sources also provide an equivalent amount of light at a reduced wattage that may be a benefit to the vehicle in terms of electrical system loading. Many of the visual effects of the low- and high-mounted beacons can be achieved using LED light sources.

Signal Colors

It is recommended that only amber lighting and white lighting be used in maintenance vehicles, with amber being the predominant color. These colors provide increased detectability and are least confused with other on-road activities such as law enforcement and emergency response.

Light Type Selection

Flashing Lights

It is recommended that the predominant light pattern be flashing. A pattern that alternates from one side of the vehicle to the other is preferable to one in which lights on both sides of the vehicle are flashing at the same time. It is also recommended that a slower flash frequency be used, because there was better response to the longer flash durations (as compared to the short flash durations required by high flash frequencies). Research has shown that a flash rate of 1 Hz is preferable to 4 Hz. A flash pattern such as a double flash or a pattern similar to that of a rotating beacon provides an appearance that enables vehicle identification and should improve response. A rotating beacon provides the appearance of flashing, and when two beacons are used, they rarely appear to be synchronized.

Steady Lights

It is recommended that, if a steady (continuous burning) light is used on the vehicle to meet federal vehicle lighting requirements (the most recent should be consulted), it should be used only as a supplement to the flashing light systems. Because steady lights have many other vehicle uses such as clearance indicators, brake lights, and vehicle headlights, they should not be used to warn drivers of the presence of maintenance vehicles.

Lighting Layout and Positioning

In the layout of the vehicle lighting, positioning the lighting such that it appears against a portion of the vehicle and not against the sky will provide a consistent contrast and will allow for increased daytime and nighttime conspicuity. However, this configuration limits the ability of the light to be seen from all directions. For example, a rotating beacon placed on top of a vehicle will lose some of its conspicuity when viewed against a daytime sky, especially with the sun behind it. This effect can be mitigated by use of flat-mount LEDs or strobe lights mounted against a solid surface. It may thus be necessary to replicate the lights at the front, back, and sides of the vehicle. Lighting that is viewable from 360° around the vehicle (providing light to all angles of approach) will enhance the safety of the crew.

The lighting system should be positioned such that the light does not cause excessive glare to approaching and passing drivers. Similarly, the light should be placed away from the tail lights of the vehicle to allow those lights to be seen. Therefore, the lights should be mounted high on the vehicle above the typical eye height of other drivers.

The lights should also be placed to outline the vehicle (i.e., on either side of the vehicle and on any portion of the vehicle that extends beyond the lane such as a plow blade or a trailer extension).

Retroreflective Tape

It is recommended that retroreflective tape should be used as a supplement to a flashing warning-light system. Such tape can be used to identify vehicle shape, but should not be used as the only warning system on the vehicle.

Effective Intensity Requirements

As discussed, the effective intensity of the warning-light system is limited at a minimum in terms of the conspicuity of the maintenance vehicle and at a maximum by the glare apparent to other drivers. Nighttime and daytime requirements are different and may require two alternative warning-light systems or a means to attenuate the light at night. The photometric limits for daytime and nighttime (listed in Table 1) were developed in a screening experiment based on the Form Factor method and then verified by the performance experiment. These values represent the total light output limits for the warning-light system on each of the approach sides of the vehicle (i.e., these limits apply to the sum of the output from the lighting on each of the rear, sides, and front of the vehicle). For lights that flash asynchronously, the sum represents the maximum value for those lights that are simultaneously illuminated. For example, if there are two light sources of equal power flashing on the rear of a vehicle asynchronously, only one of the lights is counted in the total because both are not simultaneously illuminated. However, if two pairs of lights are used and two are illuminated simultaneously, two of the light sources are included in the sum. A higher effective intensity may be required for vehicles that are primarily used in urban and visually complex environments.

Table 1. Recommended photometric limits for warning light systems on each approachable side of a vehicle.

Light Source	Intensity (by Form Factor Method)		
	Daytime	Nighttime	
	Minimum	*Minimum*	*Maximum*
Halogen	3500 cd	900 cd	2200 cd
LED	4000 cd	1650 cd	—
Strobe	3500 cd	1200 cd	2200 cd

Note that a maximum value for the LED sources was not found.

Because most roadway vehicles are used both in the day and at night, it is important to note the difference between the daytime and nighttime system. The capability to either dim the lighting available or switch off some lighting for nighttime operation would be an important addition to the warning-light system installed on the vehicle.

The values identified in Table 1 are specified using the Form Factor method (*28*) as the metric for effective intensity. The Form Factor method evaluates the light output from the flashing source in terms of the maximum intensity and the energy output of the source. The effective intensity I_{eff} of a flash pulse $I(t)$ is given by:

$$I_{\text{eff}} = \frac{I_{\max}}{1+\dfrac{a}{F\cdot T}}; \quad F = \frac{\int_0^T I(t)\mathrm{d}t}{I_{\max}\cdot T}, \tag{1}$$

where F is the Form Factor, a is a visual time constant (0.25), and I_{max} is the maximum of the instantaneous luminous intensity $I(t)$. It is recommended that this method be used for evaluating the light source as part of the selection method for the light sources.

Sample Specifications

A sample specification for the warning-light system is provided here. Each DOT is encouraged to develop its own specification based on its needs and the practitioner's experience; however, this document can be used as a reference to define the physical, functional, and performance requirements for the warning-light systems on the vehicles.

It is the policy of the DOT to maintain warning-lighting systems on all roadway operations vehicles. This system is provided in order to maintain the safety of the vehicle operator, pedestrians or personnel located adjacent to the vehicle, and the operators of the vehicles approaching or passing the roadway operations vehicles.

Physical Requirements

1. The warning-light system should be visible from all angles of approach of the vehicle: specifically, the front, rear, and both sides of the vehicle. Three hundred and sixty degrees of visibility of the lighting system must be provided.
2. Multiple light sources should be provided such that the outline of the vehicle is visible, including any obstacle attached to the vehicle such as a blade or a trailer.
3. The lighting system should be located as high on the vehicle as possible to both provide the outline of the vehicle and reduce the direct light into an approaching driver's line of vision. This location will also allow approaching drivers to more clearly see the vehicle's standard lights (such as brake lights).
4. For any portion of the lighting system that is visible against the sky (such as a beacon on the roof of the vehicle), a background should be provided to control the light appearance. This background may be a shield or a part of the vehicle. The shield may be mounted over or around the light source to maintain the 360° of visibility. The background should extend 100% of the width or height of the light source to each side and above the lighting unit.
5. The use of retroreflective tape should be used and should be compliant to federal regulations. However, this tape should be used as a supplement to the lights described previously.
6. The lighting system must be durable and weatherproof.

Functional Requirements

1. The lighting system must provide 360° of visibility around the vehicle.
2. The warning-light system should be predominantly flashing. Steady burning lights can be used to supplement the flashing-light system, but should not be considered the primary lighting system.
3. The warning-light system on the vehicle should be composed of amber or white lighting, with amber being the predominant color.
4. On the rear of the vehicle, the lighting system must provide at least two lights, one on each side of the vehicle, that flash in an asynchronous manner. The flash should have a frequency between 1 and 4 Hz.
5. It is desirable that the asynchronous lighting system on the rear of the vehicle be combined with a rotating or a simulated rotating beacon to provide 360° of visibility.
6. The light source used can be a halogen, strobe, or LED type. Note that the performance limitations of these may affect choice. The LED type may provide equivalent performance at a lower power requirement.

Lighting Performance Requirements

1. The total of effective intensities provided from all of the lights provided to each viewing angle of the vehicle should be limited to the values provided in Table 1 of the proposed guidelines. These values are effective intensity measured by the Form Factor method.
2. Two lighting levels must be provided (a daytime and a nighttime system) as specified in Table 1. The lighting levels can be achieved by either adding lighting for daytime or dimming lighting for nighttime. An auto-switching function should be considered.

APPENDIXES

The appendixes to this report (listed below) are not published herein but are available on the TRB website at www.trb.org/news/blurb_detail.asp?id=9632:

- Appendix A. Literature Review
- Appendix B. Identification of Relevant Factors
- Appendix C. Photometric Characterization Experiment
- Appendix C1. Table of Lights and Light Characteristic Summaries
- Appendix D. Static Screening Experiment
- Appendix D1. Screening Experiment Informed Consent and Questionnaires
- Appendix D2. Participant Characteristics and Questionnaire Results
- Appendix D3. ANOVA Results for All Comparisons in Static Screening Experiment
- Appendix E. Performance Experiment
- Appendix E1. Performance Experiment Information Sheet and Debriefing Form
- Appendix E2. Performance Experiment Questionnaire
- Appendix E3. ANOVA Results for All Comparisons in Dynamic Performance Experiment

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation