Lighting and Visual Information for Vulnerable Road User (VRU) Safety: An Introductory Review
Lighting and Visual Information for Vulnerable Road User (VRU) Safety: An Introductory Review

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Executive Summary

Injuries and fatalities among pedestrians, cyclists, scooterists, highway road workers, and safety and emergency personnel—often referred to as vulnerable road users (VRUs)—continue to rise at alarming rates worldwide. As new modes of transportation continue to emerge, the safety of all shared road users is of critical concern.

Human drivers and highly automated to fully autonomous vehicle systems must be able to detect, identify, and make appropriate judgments about the presence and intentions of these VRUs. Lighting systems have been identified as one aspect of a multifaceted approach to enhance the visibility of VRUs and reduce crash risks.

Commissioned by the Vulnerable Road User Safety Consortium™ (VRUSC) and conducted by the Light and Health Research Center (Icahn School of Medicine at Mount Sinai), this study evaluates the effectiveness of lighting and visual information systems in enhancing VRU safety.

As the first step in a multiyear study, this white paper summarizes published research on lighting and markings as perceived by human drivers and machine vision systems.

Outcomes of the synthesis include:

- Identification of some preliminary guidelines for the intensity, color, temporal, and spatial characteristics of lighting and visual information that may be useful in preventing crashes involving VRUs.
- Knowledge gaps to be addressed with subsequent research, including the need for standardized lighting specifications and further research tailored to VRUs’ unique needs.

The study underscores the importance of lighting in making VRUs visible to other road users and highlights the effectiveness of various lighting devices in conveying VRUs’ presence, location, and intent. It examines active (e.g., lights) and passive (e.g., reflectors) systems, focusing on ensuring intelligibility to human drivers and machine vision systems used in automated and highly automated vehicles.

Proposed next steps include investigating intensity levels suitable for daytime and nighttime, and studying lighting interactions with camera-based systems. The findings aim to inform stakeholders in VRU safety and guide the development of research agendas and strategies for effective and safe VRU lighting systems.

Risks faced by vehicle non-occupants remain a substantial public health issue. By delving into the diverse factors contributing to these crashes and potential countermeasures, the VRUSC seeks to provide invaluable insights to inform pragmatic, evidence-based potential countermeasures that contribute to a safer, more equitable and cooperative coexistence for all shared road users.
Introduction

VRUs include pedestrians, cyclists, scooter riders, highway road workers, and safety and emergency personnel, and others who share the road with vehicles but are not enclosed or protected by the structure of a vehicle. In the past decade, VRUs are increasingly at risk of being injured or killed in crashes. For example, the number of pedestrian fatalities in the U.S. between 2012 and 2021 increased by 53% (NHTSA, 2023a), and the number of cyclists killed in crashes between 2011 and 2020 increased by 32% (NHTSA, 2023b).

It is generally recognized that lighting systems may reduce crashes involving VRUs (Kwan and Mapstone, 2006; Lahrmann et al., 2018) by helping the VRU see the environment and by increasing the likelihood the VRU is seen by other road users. Lighting devices can alert other road users about the presence of the VRU, convey information about the VRU’s location and present status, and may provide cues to other road users about the intent or future status of the VRU.

Lighting and visual information for VRUs includes illumination that helps the VRU see along their current path so that they can avoid hazards. Lighting systems often also help convey the VRU’s presence to other roadway users, which seems to be the primary intention of VRUs when they use lighting (Setiawan, 2009; Pietrantonio, 2021). Signal lights, whether steady burning or dynamic, are also used to share information about the VRU’s presence or intent. Passive visual information systems, such as reflectors, can also serve these functions. It’s important that lighting and visual information for VRUs need to be intelligible not only for human drivers, but for cameras as part of machine vision systems increasingly used in driver assistance systems and automated vehicles.

This white paper summarizes applied research studies on lighting and human factors, technical investigations of lighting as it interacts with machine vision systems, and several codes and regulations for VRU lighting and visual information to identify common trends regarding the effective use of visual elements to enhance VRU safety and to ascertain gaps in collective knowledge so that research in this area can focus on filling those gaps. This white paper includes an annotated bibliography with summaries of the key findings from each of the studies and information sources that were reviewed.

To understand the needs and requirements for lighting and visual information as they impact VRU safety, several activities were undertaken:

- A review of international, national, state, and municipal codes and requirements for VRU lighting and visual information.
- A review and summary of VRU lighting research studies related to human factors.
- A review and summary of VRU lighting and interactions with machine vision.
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Illustrative Review of National, State, and Municipal Codes

While a comprehensive review of codes and regulations related to the use of lighting by VRUs was beyond the scope of this review, representative examples of codes from different jurisdictional levels were reviewed. As will be seen, there are substantial areas of overlap among the codes at all levels.

European Union: The European Commission states that bicycles must “be equipped with a red reflecting device at the rear, and devices ensuring that the bicycle can show a white or yellow light at the front and a red light at the rear.”

Germany: In Germany, bicycles must have one or two white, front-facing headlights. Every headlight must be adjusted so that it “does not blind other road users.” A forward-facing white reflector is also required. Bicycles are also required to have a red taillight and a red reflector that is not triangular facing the rear. Pedals must have yellow reflectors in front and rear, and wheels should be equipped with white reflectors. Wheel spokes must also be reflectorized white with two opposite spokes reflectorized yellow. Front-facing lights and reflectors are required to have a mounting height between 0.4 and 1.2 m (16 to 47 in); for rear-facing lights and reflectors, the mounting height must be between 0.25 and 1.2 m (10 to 47 in). Bicycles more than 1 m (39 in) wide must have two headlights and two taillights.

Norway: In Norway, scooters are required to have a front-facing headlight that is either white or yellow in color. The headlight may be steady burning or flashing but must not dazzle other road users. Scooters are also required to have a steady-burning or flashing red light in conjunction with a red reflector facing the rear of the scooter. The code requires all lights to be visible up to 300 m (~1000 ft). When flashing, lights must flash at a frequency of 120 Hz. This requirement stipulates that lights may be attached either to the scooter itself or to the person riding it, except that the lights may not be attached to the rider’s head.

United States: In the U.S., bicycles are required to have a white reflector facing the front, white or yellow reflectors on the front and rear of each pedal, and a red reflector facing the rear. The front wheel should be equipped with reflectors mounted to the spokes or with reflectorized tire walls or rims, either white or yellow in color. The rear wheel should also be equipped with reflectors mounted to the spokes or with reflectorized tire walls or rims, but either white or red in color. All reflectors should meet minimum retroreflectivity values specified in the Code of Federal Regulations (§1512.18).

Oregon: In Oregon, bicycles are required to have a white light on the front of the bicycle that is white in color which must be visible up to 500 ft (150 m) in front of the bicycle. On the rear of the bicycle, a red light or reflector is required which must be visible up to 600 ft (180 m) behind the bicycle.

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5 OregonLaws. (n.d.) Violation of bicycle equipment requirements; Penalty (ORS 815.280). https://oregon.public.law/statutes/ors_815.280
Columbus, OH: The municipal code for lighting on bicycles in Columbus includes both pedal-powered and motorized bicycles. Bicycles are required to be equipped with a white-colored headlight at the front that is visible up to 500 ft (150 m) ahead of the bicycle, and up to 300 ft (90 m) to either side. Bicycles must also have a rear-facing red reflector that is visible between 100 and 600 ft (30 to 180 m) behind the vehicle. In addition to the reflector (not as an alternative), there must also be a steady-burning or flashing red light mounted on the back of the bicycle, and the red light must be visible from a distance up to 500 ft (150 m) behind the bicycle.5

New York City, NY: In New York City, bicycles are required to be equipped with a headlight that is white in color and used between dusk and dawn. Bicycles are also required to have a red taillight. In addition, it is required that bicycles are equipped with reflectors attached to the spokes of each wheel or to have tires with reflective sidewalls.7

San Antonio, TX: Bicycles in San Antonio are required to use a white headlight that is visible from up to 500 ft (150 m) in front of the bicycle between dusk and dawn. In addition, a red light must be installed on the rear of the bicycle that is visible from distances up to 500 ft (150 m) behind the bicycle. In place of the red light, a red reflector may be installed instead, and it must be visible at all distances between 50 and 300 ft (15 to 90 m) behind the bicycle.8

Tempe, AZ: Motorized scooters used along public roads and streets in Tempe are required to have a white-colored headlight that can be seen at distances up to 500 ft (150 m) ahead of the scooter. In addition, the scooter must be equipped with a red light or reflector that is visible at distances between 50 and 300 ft (15 to 90 m) behind the scooter.9

As can be seen by these examples of international, national, state, and municipal codes for VRU lighting, the primary emphasis of each of these codes is on making the VRU’s vehicle visible to other road users. Each of the codes follows similar “white in the front,” “red in the back” color requirements, and stipulates various (and often different among different jurisdictions) distances at which lights or reflectors should be visible to other road users. For rear-facing visual elements, sometimes a light and a reflector are required (e.g., Norway and Columbus), while at other times (e.g., Oregon, Tempe, San Antonio), a light or a reflector may be used.

Notwithstanding minor differences, like the “and/or” requirements for red lights/reflectors, many of the regulations described above have a basic similarity regarding color coding and distance requirements for the visibility of the lights on the front and rear of the bicycle. Interestingly, while many of the visibility requirements also provide a quantitative metric (e.g., visibility distance) for visibility of the lights and reflectors, specifying their performance based on visibility distance is not particularly useful because the visibility of a light source depends upon its luminous intensity and the background luminance (CIE, 1980). The background luminance can vary widely depending upon whether the environment in which the light source is viewed is bright (e.g., urban) or dark (e.g., rural). It should also be noted that the sensitivity of the observer (the human visual system or a camera-based sensor) will also impact the visibility of a light source or reflective element.

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6 Signal devices on bicycle and mobility device; brake, § 2173.05 (n.d.). http://columbus-oh.elaws.us/code/coor_title21_ch2173_sec2173.05
As addressed in a subsequent section, some investigations of the intensity of VRU lighting have explored the optimal photometric characteristics of these devices for different situations that can be measured objectively (e.g., in candelas). With the exception of Germany, many requirements also permit the use of flashing lights, but, in general, this is an option, not a requirement, and it is not obvious from the codes whether, or when, there is a benefit of using flashing in certain circumstances over steady-burning lights. Flashing lights very clearly have important attention-getting benefits, but can impair one’s ability to judge relative speed or distance (Rea and Bullough, 2016) and make it more difficult to detect pedestrians in their vicinity (Bullough et al., 2022b) under certain conditions.
Review of Published Literature

In the review of literature for the present study, published reports on human factors responses to lighting in the context of VRUs and on the interactions of lighting and visual information with machine vision have been evaluated in terms of their functions; that is, in terms of the responses they are designed to elicit from other road users. Examples of VRU lighting functions include:

- Conveying the presence of the VRU somewhere in the road user’s vicinity (detection).
- Conveying the location (or distance ahead/behind) of the VRU.
- Conveying the size of the VRU.
- Conveying the intent or future actions of the VRU.

In the research studies that have evaluated lighting and visual information for VRUs, there is usually some manipulation of the characteristics of the lighting itself. These characteristics include:

- The intensity (or brightness) of the light or visual element.
- The color of the visual element.
- The size of the light array or visual element(s).
- The shape or profile formed by the light(s) or visual element(s).
- The temporal properties of the light/visual element (e.g., flashing).
- The spatio-temporal properties of the light/visual element (e.g., animation).

The examples of VRU lighting functions in the list above focus on the information that lighting is supposed to provide to other road users so that they can formulate appropriate responses by stopping, slowing down, changing lanes, or other driving behaviors intended to avoid a collision with the VRU, while the latter list of characteristics describes the degrees of freedom that the lighting system designer has, in order to create different visual stimuli. It can be thought of as the artist’s palette in the design of lighting systems. While the intensity and the color are often the factors that most commonly come to mind when considering the characteristics of lighting for VRU safety, the spatial and temporal characteristics can be useful in providing information to road users about the type of situation that is being encountered along the roadway.
To identify appropriate studies for this review, articles and reports identified by members and staff of the VRUSC, consisting of subject matter experts from across the globe with substantial experience in VRU safety research and product development, were included, and several research databases were searched, such as:

- International Traffic Safety Data and Analysis Group (IRTAD).
- Google Scholar.
- SAE Mobilus.
- Transport Research International Documentation (TRID).

Key points from each of the studies that were identified and reviewed are listed in the annotated bibliography at the end of this report.
**VRU Lighting and Human Factors**

*Table 1* summarizes the key findings from the human factors literature review as a matrix presented over several pages. Each column in the matrix relates to the distinct functions that VRU lighting and visual information can serve for other road users: supporting detection by conveying the VRU’s presence, conveying the location of or distance to the VRU, conveying the VRU’s physical size, and conveying the intended action of the VRU. Each row in the matrix indicates the degrees of freedom or the different characteristics of VRU lighting that can be modified to achieve the various functions: intensity, color, size, shape, temporal, and spatio-temporal characteristics. Each study can be located at the intersection of one (or more) functions and lighting characteristics.

While many of the studies summarized in *Table 1* and in the annotated bibliography pertain directly to VRU lighting and visual information, others come from other transportation domains, including vehicle lighting, emergency warning lights, aviation lighting, and others.

**TABLE 1 Summary of published studies on VRU lighting and human factors**

<table>
<thead>
<tr>
<th>Lighting Characteristics ↓</th>
<th>Intended Impacts</th>
<th>Convey Location/Distance</th>
<th>Convey Size</th>
<th>Convey Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>• Lights more effective than reflectors (Bhagavathula et al., 2020).</td>
<td>• Change in brightness conveys distance (Westerhuis et al., 2021).</td>
<td>• None identified.</td>
<td>• Road projections → improved awareness by others of intent to turn (Hamm and Hinterwaelder, 2020).</td>
</tr>
<tr>
<td></td>
<td>• Lower nighttime intensity → faster identification (Bullough et al., 2022b).</td>
<td></td>
<td></td>
<td>• 2.5 cd/m² luminance is visible but appears dim (Hamm and Hinterwaelder, 2020).</td>
</tr>
<tr>
<td></td>
<td>• Running lights → fewer collisions (Fotios and Castelton, 2017).</td>
<td></td>
<td></td>
<td>• A segmented signal light communicated intent to stop/turn (Westerhuis et al., 2021).</td>
</tr>
<tr>
<td></td>
<td>• Taillights and vests → more reported crashes, likely confounded (Hagel et al., 2014).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Intensity &gt;150 cd reduces nighttime identification (Kersavage et al., 2018).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Higher intensity needed for daytime visibility (Pietrantonio, 2021).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Optimal intensity: 25 cd at night, 250 cd at day (Rea et al., 2018).</td>
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<tr>
<td></td>
<td>• Self-illuminated elements have wider visibility angles than reflectors (Tarkowski et al., 2021).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting Characteristics</td>
<td>Facilitate Detection</td>
<td>Convey Location/Distance</td>
<td>Convey Size</td>
<td>Convey Intent</td>
</tr>
<tr>
<td>--------------------------</td>
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<td>---------------</td>
</tr>
<tr>
<td><strong>Color</strong></td>
<td>• Specific colors for optimal conspicuity depend on environment (Brown et al., 2021).</td>
<td>• None identified.</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td></td>
<td>• Bluer colors increase discomfort glare (Bullough et al., 2022a).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Fluorescent colors might reduce daytime crashes (Kwan and Mapstone, 2006).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>• None identified.</td>
<td>• Multiple lights convey motion/closure better than single light. (Rea and Bullough, 2016).</td>
<td>• Reflective tape along the side of a motorcycle frame helped improve identification at intersections (Khalid et al., 2020).</td>
<td>• None identified.</td>
</tr>
<tr>
<td><strong>Temporal: Flash Rate</strong></td>
<td>• Rapid onset improves detection (Bullough, 2017).</td>
<td>• High/low modulation flashing improves closure detection. compared to on/off flashing (Rea and Bullough, 2016).</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td></td>
<td>• Blinking lights → high conspicuity (Abdur et al., 2021).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Fast flash rate → improved detection during day, moderate flash rate during nighttime (Bhagavathula et al., 2020).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Cycled crosswalk lights improved pedestrian detection (Bullough and Skinner, 2017).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Synchronized/slower flash rate → improved detection (Bullough et al., 2022b).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Steady lights → less bothersome, flashing lights → improved detection from long distance (Kircher and Niska, 2021).</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It can be seen by examining Table 1 that some cells in the matrix list numerous studies and publications, such as the cell corresponding to the first row (intensity) and left-most column (detection), indicating that there have been multiple investigations of the impacts of light source intensity on detection. In contrast, other cells (which are shaded gray in Table 1 and state “None identified”) have no publications listed in them, indicating that the review did not identify any studies related to certain factors.

<table>
<thead>
<tr>
<th>Lighting Characteristics ↓</th>
<th>Intended Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Facilitate Detection</td>
</tr>
<tr>
<td>Spatio-Temporal: Animation</td>
<td>- Reflectors on joints → longest detection distances (Hemeren et al., 2017).</td>
</tr>
<tr>
<td></td>
<td>- Biomotion improves identification (Kwan and Mapstone, 2006).</td>
</tr>
<tr>
<td></td>
<td>- Biomotion improves detection distance (Wood et al., 2022).</td>
</tr>
<tr>
<td>Shape/Profile</td>
<td>- Reflective tape on rear of bicycle frame improved detection over reflectors on pedal cranks (Costa et al., 2017).</td>
</tr>
<tr>
<td></td>
<td>- Triangular array of lights → improved conspicuity (Edewaard, 2020).</td>
</tr>
<tr>
<td></td>
<td>- Yellow jacket → 38% reduction in crash rate (Lahrmann et al., 2018).</td>
</tr>
</tbody>
</table>
Some of the key findings in Table 1 found differences in optimal intensity of light source for daytime and nighttime. For example, Rea et al. (2018) found that flashing barricade lights could be readily detected without creating distraction or discomfort glare when their peak luminous intensity was 250 cd during the daytime and 25 cd during the nighttime. A related and consistent finding comes from the study by Kersavage et al. (2018) who showed that when the peak intensity of a flashing light on a parked vehicle exceeded 150 cd at night, the ability of drivers to see a pedestrian in the vicinity of the light was reduced.

Regarding the color of lights and visual elements, Bullough et al. (2022a) showed that lights producing more short-wavelength or “blue” spectral content were judged by drivers as creating more visual discomfort at night, which could impact how and where drivers look along the roadway in the presence of such lights. During daytime traveling, Kwan and Mapstone (2006) reported that the use of reflective apparel with fluorescent colors was associated with a reduction in crashes involving VRUs.

Related to the size of VRU lighting and visual information, Rea and Bullough (2016) found in a laboratory study that an array of two or more flashing lights was more effective than a single light at helping drivers detect when they are closing in behind a slower-moving vehicle (closure detection) because the array of lights has a larger change in visual angular size as the distance changes, compared to a single light. The shape of an array of lights or other visual elements can also be helpful in identification of a VRU or VRU vehicle (Edewaard, 2020), as can the size of these elements (Khalid et al., 2020).

The temporal characteristics of lighting can also impact visual responses. For example, a light source that has a rapid onset time when power is applied, such as a light-emitting diode (LED), will be detected more rapidly (Bullough, 2005) than an incandescent lamp, which can take 200 ms or longer to reach its maximum light output upon the application of power. For flashing lights, when sources modulate between “high” and “low” levels of output rather than flashing between completely “on” and completely “off,” drivers can more readily detect closure (Rea and Bullough, 2016). It was also found in a study of emergency vehicle lighting that when the flash rate of the lights was slower, or when multiple lights flashed in a synchronized manner with each other, drivers could more quickly identify the location of a pedestrian within a roadway scene (Bullough et al., 2022b).

Regarding animation (or spatio-temporal) characteristics of VRU lighting and visual information, Black et al. (2021) found that locating reflective visual elements along the limbs of pedestrians to convey a sense of “biomotion” to approaching drivers resulted in more accurate identification of the walking direction of pedestrians. Accuracy was lower for reflective elements that were attached to the torso only.

Table 1 also illustrates where apparent gaps in knowledge may exist. More studies are needed regarding the color, size, or flash rate of VRU lighting and the ability to convey VRU intent to stop, slow down, or turn. Additionally, there is a dearth of studies on the lighting characteristics that best convey information about the size or type of VRU or VRU vehicle.
VRU Lighting and Machine Vision Systems

In a similar format as in Table 1, the key findings from the review of literature pertaining to VRU lighting and machine vision systems are shown in Table 2. Overall, fewer articles and reports were identified for this portion of the literature review than for the review on human factors.

<table>
<thead>
<tr>
<th>Lighting Characteristics</th>
<th>Intended Impacts</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Facilitate Detection</td>
<td>Convey Location/Distance</td>
<td>Convey Size</td>
</tr>
<tr>
<td>Intensity</td>
<td>• None identified.</td>
<td>• Use of lights for communications is hampered by narrow distributions (Viriyasitavat, 2013).</td>
<td>• None identified.</td>
</tr>
<tr>
<td>Color</td>
<td>• Color/hue is a cue for identifying type of signal/sign (Yuan et al., 2016).</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td>Size</td>
<td>• None identified.</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td>Temporal: Flash Rate</td>
<td>• Pulse width modulation can interfere with cameras and other detectors (Bullough, 2017).</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td></td>
<td>• Image artifacts between cameras and LEDs include banding, brightness differences, and signals that appear “off” (Deegan, 2018).</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td></td>
<td>• Cameras can exhibit flicker artifacts at frame rates as high as 500 Hz (Yabuuchi et al., 2020).</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td>Spatio-Temporal: Animation</td>
<td>• None identified.</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
<tr>
<td>Shape/Profile</td>
<td>• Fitting to circular edges in images helps identify bicycles (Aderum et al., 2019).</td>
<td>• None identified.</td>
<td>• Camera systems use symmetry of left/right headlights and taillights to identify vehicles (Jensen et al., 2016).</td>
</tr>
<tr>
<td></td>
<td>• Algorithms use shapes to identify signs/signals (Yuan et al., 2016).</td>
<td>• None identified.</td>
<td>• None identified.</td>
</tr>
</tbody>
</table>
Among the key findings related to the intensity of VRU lighting and visual information, Viriyasitavat (2013) reported that the intensity distribution of lights that are visible to human drivers can sometimes be too narrow for machine systems to detect reliably. This underlies the importance of tailoring the intensity and distribution of lights for both sets of observers.

As reported by Yuan et al. (2016), many machine vision systems can use the hue or color information in recorded images to identify signs. Stop signs, for example, are distinctly red, and this can be a salient visual cue for machine vision. Similarly, algorithms for vehicle-based camera systems also use the shape of a sign as a visual cue; this, like color, helps in the identification of stop signs and can assist identifying other signs with unique shapes such as a yield sign (Yuan et al., 2016). These properties of machine vision systems could also be helpful in identifying VRU lighting and visual information systems reliably.

One issue has emerged with the advent of LED lighting systems that use pulse width modulation (PWM), or the rapid flickering of lights at frequencies of 100 Hz or higher, so that they appear to be steady burning. When these lights have a duty cycle below 100%, meaning that they are "on" for less than 100% of the time, the apparent brightness of the light matches that of a steady-burning light with an intensity at the same percentage of the maximum intensity of the PWM-controlled light. PWM control, however, can interact with the frame capture rate of camera systems. The result is that a PWM-controlled LED lighting system may appear to be off or only partially on, or may appear to blink on and off over time, depending upon the relative frequencies of the PWM flicker and the camera’s frame rate. The lower the PWM frequency, the more likely this effect is to be observed. It has been observed even for PWM frequencies as high as 500 Hz (Yabuuchhi et al., 2020).

It should be noted that flicker (or temporal light modulation [TLM]) from PWM-driven LED lighting systems also has the potential to interact with human vision even at frequencies high enough to avoid the direct perception of flicker (>80 Hz). Stroboscopic effects (Bullough et al., 2012b) and the phantom array (Miller et al., 2023) can be perceived at PWM frequencies well in excess of 1000 Hz. The impacts of these responses on VRU safety are not well understood.

The matrix in Table 2 has a greater proportion of empty (gray-shaded) cells than Table 1. Specific knowledge gaps that these empty cells indicate are the use of size and spatio-temporal characteristics of VRU lighting to improve safety and the lighting properties that may be used with machine vision systems to reliably convey a VRU’s intended actions.


Discussion

Preliminary Conclusions

The review of published literature on VRU lighting, human factors, and machine vision systems leads to several preliminary conclusions. These are subject to change as further research is identified or carried out:

- Specifications for the brightness of VRU lighting and visual information should be made in terms of measurable photometric quantities, such as luminous intensity in candelas (cd), luminance in candelas/square meter (cd/m²), or retroreflectivity in candelas/square meter/lux (cd/m²/lx), not behavioral responses, such as visibility distances that are sensitive to ambient conditions. It is also important to specify the relevant observer (e.g., human eye or camera system) to which a specification pertains.

- Light sources should have a minimum of two different intensity settings: one for daytime and one for nighttime use.

- The use of white light sources and visual elements on the front of a VRU vehicle and red on the back will maintain consistency with most existing codes for lighting and visual information on bicycles and scooters.

- An array of light sources or elements outperforms a single source of light assisting human drivers’ ability to judge changes in the relative distance with a VRU. The larger the size of the array, the greater drivers’ sensitivity to changes in distance will be.

- The use of a unique set of spatial patterns, whether triangular, diamond, or another readily recognizable shape, might assist both drivers and machine vision systems in identifying VRUs as distinct from other road users.

- The use of flashing lights to capture attention is effective, but “high/low” flashing rather than “on/off” flashing should be used to facilitate closure detection. If multiple lights are flashed, they should be synchronized.

- As a greater number of driver assistance systems and autonomous driving systems are deployed along the road, careful attention will need to be paid to the frequency with which PWM systems are used if PWM intensity control systems will be incorporated into LED lighting.

The knowledge matrices in Table 1 and Table 2 of this report can help to guide the search for further information in other transportation domains, and to locate additional areas of research to identify optimal characteristics of lighting and visual information for improving the safety of VRUs.
Possible Next Steps

While not a comprehensive list, the literature summarized in this document points to several subsequent activities that could be undertaken to develop and improve the effectiveness of lighting and visual information for VRU safety:

- Most, if not all, research on the differing intensity levels for lighting needed during daytime and nighttime use have focused on infrastructure-based lighting (e.g., barricade lights) or lighting for emergency vehicles; the implementation of lighting for VRUs and their vehicles could vary based on different sizes, speeds, and likely locations along the roadway. Studies to investigate these factors could be performed.

- Similarly, investigations on the daytime versus nighttime intensity requirements of VRU lighting described in this report have focused on human observers, not on the capabilities of camera-based systems. It will be increasingly important to have research-based evidence supporting the performance requirements for VRU lighting to meet the needs of both kinds of observers.

- The interactions between the temporal characteristics (flashing and flicker) of VRU lighting and camera-based systems likely need to be studied in greater detail, both to understand how likely it is that these interactions can impact VRU safety, and what steps might be taken to minimize those impacts.

- Most of the studies of VRU lighting in this report have addressed the use of discrete light sources or reflectorized elements to convey visual information. As discussed by Hamm and Hinterwaelder (2020), compact light source technologies and optics have evolved to the point where projections onto the road surface are feasible means of communicating a vehicle’s status to others along the road. Initial applications have focused on using these technologies on conventional motorized vehicles to communicate with other drivers, but projections from bicycles or other VRU vehicles might be effective for enhancing VRU safety. Studies on the most efficacious configurations could be carried out.

Unlike automotive lighting, which is highly regulated and specified in detail, lighting for VRUs is, at present, codified only in a few high-level details and requirements which vary across jurisdictions. Before regulations and practices related to lighting and visual information for VRU safety can begin to be standardized, input is needed from a wide range of stakeholders, including VRU interest groups (covering pedestrians, cyclists, scooter riders, road workers, etc.), transportation departments, automotive and micromobility manufacturers, and safety experts. This report can serve as background information for stakeholders in VRU safety to develop research agendas, standards, and strategies for effective and safe lighting and visual information for VRUs.
About the Vulnerable Road Users Safety Consortium™

**VRUSC Vision:** Safer roads for all.

**VRUSC Mission:** The VRUSC is a collaborative, member-led global consortium program comprised of members and stakeholders drawn from cross-sections of the global transportation ecosystem, including vehicle, micromobility, and technology sectors. Our goal is to achieve safer roads for all, with a particular focus on cyclists, pedestrians, emergency and road workers, and other shared road users.

Contact Information

The VRUSC encourages any readers who are aware of additional research related to this topic to bring it to our attention at vrusc@sae-itc.org or via the Contact Us page at vrusc.sae-itc.org/contact. Thank you.

Join us! The VRUSC is actively seeking collaboration for work on new projects. Contact us to learn more and contribute to making a difference in shared road user safety.

To learn more about the Vulnerable Road Users Safety Consortium™, please visit the following:

- [https://vrusc.sae-itc.org](https://vrusc.sae-itc.org)
- [https://www.linkedin.com/in/lisaspellman/](https://www.linkedin.com/in/lisaspellman/)
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Contact: Lisa Spellman, Director, [lisa.spellman@sae-itc.org](mailto:lisa.spellman@sae-itc.org).
Annotated Bibliography


- A reflective marking configuration consisting of alternating red and white stripes resulted in high levels of conspicuity to drivers compared to other combinations.

- The use of blinking patterns also resulted in high levels of conspicuity relative to steady, non-blinking patterns.


- Methods for enhancing the ability of camera/sensor systems to detect and identify cyclists are described.

- Algorithmic methods, such as fitting bicycle wheels to ellipses and predicting cycling paths, are discussed.

- Benefits to automatic emergency braking (AEB) systems could increase by 10% with proposed improvements.


- Countermeasures for bicycle crashes that are recommended include speed calming, sharrow road markings, road signs, and education about “dooring” crashes.

- Bicycle-mounted lights or markings were not considered as possible countermeasures.


- Systems defined as “active” (e.g., lights mounted on bicycles) result in making cyclists more conspicuous to drivers than ones defined as “passive” (e.g., retroreflective vests, biomotion markings on clothing).

- Faster flash rates (6 to 7 Hz) of flashing lights had a larger benefit on detection during the daytime compared to nighttime, when slower flash rates (3 to 4 Hz) were most effective during nighttime.

- Pedestrians with black clothing wore retroreflective markings to provide biomotion, or applied them to legs and torso, torso only, or legs only.

- All treatments resulted in better judgments of the pedestrian walking direction than no treatment, but the biomotion treatment resulted in the highest accuracy, followed by legs and torso markings, then torso only, and then legs only.


- Rear-facing red lights mounted on handlebars, on the bicycle helmet, and retroreflectors mounted on knees and ankles (all in conjunction with a red reflector and red light) resulted in larger lateral passing distances from bicycles compared to the reflector and red light alone.

- The same systems were rated by drivers as less difficult to judge their passing distance.


- Specific colors that make motorcyclists visible depend on the environment and its conditions. Wearing black might be more conspicuous in rural areas in the daytime, whereas bright reflective colors might be more so in nighttime locations.


- Lights that “swept” from left to right or right to left resulted in drivers changing lanes in the direction of the sweeping motion earlier than lights that simply flashed on and off.


- Depending upon the speed of object motion under flickering illumination, stroboscopic effects could be detected at frequencies of up to 3000 Hz.


- Briefly flashing crosswalk lights (three 1-second cycles before remaining steady on) helped increase drivers’ ability to detect pedestrians crossing a street.

- Vertical illumination on pedestrians improved their contrast against the roadway surface.
Saturated colored signal lights (e.g., light emitting diodes [LEDs]) result in higher perceived brightness than less saturated lights (e.g., filtered incandescent sources), even when matched for intensity.

The rapid onset of LED signal lights results in shorter response times to the onset of a light.

Pulse width modulation (PWM) control of LED sources can interfere with the frequency of cameras or even moving objects, such as airplane propellers.

LED sources producing saturated color appearance (especially red and blue) result in greater perceptions by drivers of brightness than less saturated white and yellow colors.

Discomfort glare is enhanced by short-wavelength energy in blue and white signal lights compared to red and yellow.

Retroreflective materials can sometimes be bright enough at night to detract from visibility of nearby pedestrians.

Intensity levels (i.e., SAE Class 1) of flashing lights that produced no glare to drivers during the daytime were rated as glaring when presented at night without being dimmed.

Slower flashing rates resulted in increased driver confidence at night compared to faster flashing.

Synchronized flashing lights resulted in shorter detection times to a pedestrian target located adjacent to the lights compared to randomly flashing lights.

Signal lights require lower luminous intensities at night in order to be detected reliably.

Attaching reflective tape to pedal cranks was not as effective as applying it to the rear of a bicycle frame for detection and recognition by drivers.

High-visibility clothing makes cyclists more visible to drivers but may not impact how closely people drive when they pass by cyclists.

Treatments that modulate in brightness while pedaling a bicycle will improve conspicuity.

Pedestrians frequently overestimate their own conspicuity as perceived by vehicle drivers.
Collisions with light mopeds often occur because drivers are unaware of or unable to see the moped’s presence.

Light-emitting diode sources whose intensity is controlled by pulse width modulation (PWM) can exhibit differences in brightness, spatial banding, and other artifacts when viewed by cameras.

Differences in camera exposure times will result in differences in the captured images.

A test measurement procedure is outlined to identify light sources that can be susceptible to flicker-related imaging issues.

For daytime viewing, increased intensities of lights on bicycles and an increased number of lights resulted in improved ratings of conspicuity.

A triangular array of lights performed better in terms of rated conspicuity than a single seat-post light or lights on the pedal heels.

Adding a bicycle lane to a roadway can reduce crashes involving cyclists by 30% to 49%.

German "K-Mark" requirements for bicycle lighting are used in numerous European countries as a default standard.

Minimum and maximum illuminances on a plane 10 m ahead of an upright bicycle are defined to ensure forward visibility and reduce glare.

Permanent running bicycle lights appear to be associated with a ~14% reduction in injurious crashes between bicycles and motor vehicles.

Characteristics of biomotion garments that appeal to pedestrians and cyclists are described.

Not looking like a “road worker” and having zippered pockets are key elements.
Benefits of cycle-mounted conspicuity aids, such as lights on handlebars, may be more beneficial in rural than urban environments.

Reflective elements on legs and ankles have benefits over those affixed to the bicycle; movement appears to increase the conspicuity of these treatments.


Light-colored cyclist clothing during the daytime was associated with a reduction in reported crashes involving cyclists.

During nighttime cyclist-related crashes, taillights and lighter-colored clothing were counterintuitively associated with a higher risk of crashes, possibly because of over-reporting of these factors.


Both dynamic and static arrow projections from vehicle lighting onto the pavement provided helpful indications to cyclists and pedestrians about a vehicle's intended travel direction.

A luminance of 2.5 cd/m² for the pavement markings was visible, but some pedestrians and cyclists reported that they were perceived as appearing dim.


Clothing with reflective elements resulted in the longest detection distances by drivers when they were mounted along the joints of arms and legs to provide biomotion cues.


Systems using cameras often rely on symmetry of headlights/taillights to identify vehicles.

Color tones for different, nominally equivalent colors can differ.

Oblique angles make it difficult for systems to recognize some configurations.

Synchronization issues between LED duty cycles and camera frame rates can make all or part of a signal display look “off.”
Identification distances to pedestrian targets at night in the presence of nearby flashing yellow lights were nearly constant (>800 ft) when pedestrians wore reflective vests.

For pedestrians without reflective vests, identification distances were shorter (<400 ft) and decreased as the peak flashing light intensity increased above 150 cd.

Identification distances were unaffected by the flashing frequency (1 Hz or 4 Hz) of the lights.

Adding a length of reflective tape along the side of a motorcycle’s frame improved drivers’ ability to identify the motorcycle, especially when the motorcycle was located along the adjoining road of an intersection.

Steady-burning rear lights on bicycles are perceived as less bothersome than flashing lights by drivers approaching from behind with one exception.

When bicycles are located more than 300 m ahead of a vehicle, flashing lights on the rear of the bicycle result in improved detection.

Mounting position of lights on bicycles did not affect drivers’ willingness or unwillingness to turn in front of an approaching bicyclist (gap acceptance).

A review of studies of crashes involving pedestrians and cyclists found daytime crashes could be reduced with fluorescent material colors.

Nighttime crashes could be reduced by using lights (including flashing lights) and retroreflective materials in locations supporting the perception of biomotion.

An analysis of self-reported crash reports from cyclists who did and did not wear a yellow cycling jacket was made.

Riders with the jacket had a crash rate that was 38% lower than those without it.

The phantom array effect from rapidly flickering sources can be detected at frequencies of 6000 Hz or higher.

- Odd ratios for adult cyclists involved in collisions were estimated for cyclists with and without conspicuity aids, such as reflective or fluorescent clothing.

- Unadjusted odds ratios were the same regardless of conspicuity aids.

- Odds ratios adjusted for age, sex, and crash histories indicated a slightly greater risk with conspicuity aids, but likely this is due to confounds, such as reporting bias or differences in locations.


- New technologies for easily creating signal lights with varying shapes include light guides, organic LEDs, and holograms from diffractive optical elements.


- Fatal crashes involving pedestrians increased by 53% between 2012 and 2021.

- More than three-quarters of pedestrian fatalities occur during hours of darkness.


- Fatal crashes involving cyclists increased by 32% between 2012 and 2021.

- Over half of cyclist roadway fatalities occur during hours of darkness.


- A seat-post-mounted light was developed based on surveys and interviews with cyclists.

- Higher intensities were needed during the daytime to ensure the lights were visible.


- Closure detection times to a pair of flashing lights were significantly shorter than to a single flashing light.

- Flashing lights that modulate between “high” and “low” result in shorter closure detection times than lights that modulation between “on” and “off.”
Peak luminous intensities of 25 cd were sufficient for adequate visibility by drivers at nighttime, although 250 to 750 cd was necessary to ensure daytime visibility.

Sequential and synchronized flashing of multiple lights resulted in improved information and reduced discomfort glare to drivers.

In a simulator study, participants were able to detect bicyclists wearing a yellow cycling jack at greater distances than those without jackets.

The benefit was negligible unless the viewing conditions already permitted visibility of the cyclist from a large distance, limiting the benefit of the yellow cycling jacket.

Reflective markers on bicycle pedals helped drivers detect a cyclist most when the cyclist was actively pedaling the bicycle, resulting in alternating visibility of the markers.

Because the visibility of reflective elements depends strongly on the lighting geometry, self-illuminated elements are recommended to ensure drivers can detect cyclists from a wide range of angles.

The ability of an LED signal light on a scooter or similar vehicle is limited by its optical distribution, meaning receivers of visible light communication signals at oblique angles might not receive accurate information from the light.

To judge speed perception of a bicycle at night, drivers rely on changes in brightness and in visual angle between lights (when multiple lights are present).

E-bicycles and conventional bicycles are difficult to distinguish visually.

A custom bicycle light communication system was developed to show turning intentions, braking status, and riding speed to other road users; a majority of test observers rated the visibility of each function as good.

- Helmet-mounted lights resulted in longer detection distances compared to bicycle-mounted lights.
- Retroreflective strips worn on the legs resulted in greater detection distances of cyclists than no reflective strips.
- The benefit of both treatments was enhanced when both were present.


- Light-emitting diode traffic lights can exhibit temporal flicker artifacts (changes in image brightness) even with a camera recording at 500 fps.
- An algorithm that samples multiple frames and “fills in” images where flicker artifacts make a light invisible is described for improved camera detection and recognition of traffic lights.


- Driver assistance systems use camera-based systems to recognize signs and signals within images.
- Algorithms for identifying signs and signals based on brightness differences, aspect ratios of stimuli, average color, and degree of circularity (i.e., shape, for roundel traffic signal lights) are described that use support vector machine (SVM) models.