STATE OF THE PRACTICE REVIEW

Human Factors Considerations for LED-Enhanced Static Traffic Signs

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Introduction

Traffic signs communicate important information that drivers rely on to safely perform driving tasks. Because of their critical role, it's crucial that drivers are able to detect, recognize, and respond to signs with sufficient time and distance to do so safely. When signs are difficult to detect or not easily distinguishable within a visually complex environment, drivers may miss critical information, which can compromise safe driving performance. As a result, enhancing sign visibility and conspicuity are key components in roadway and traffic control design.

There are a variety of treatments that can be implemented to improve sign conspicuity, including the use of retroreflective materials, the removal of unnecessary or redundant signs, and increases in sign size. In the early 2000s, light-emitting diodes (LEDs) were first introduced within static traffic signs to draw drivers' attention to particularly important information (Bert, 2021).

From a human factors perspective, the effectiveness of LED-enhanced static signs depends on how drivers perceive, interpret, and respond to these visual stimuli under real-world driving conditions. This report explores literature on the use of LEDs within static signs, examines how their use relates to human factors principles, and describes current guidance and state practices regarding their implementation.

Background

Traditional traffic signs provide crucial information that drivers must be able to detect, read, and interpret in a timely manner to support safe driving behavior. In visually complex roadway environments, signs may be overlooked, increasing the risk that important information is missed. To address this challenge, conspicuity-enhancing treatments, such as LEDs within static signs, have been implemented, with their use first introduced in the 2003 Edition of the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) and more substantial provisions on their appropriate use incorporated in the 2009 Edition.

The MUTCD establishes uniform national criteria for the use of traffic control devices to promote consistency nationwide. The MUTCD provides extensive provisions on the placement, color, size, location, and spacing of static signs, as well as proven treatments to enhance conspicuity. However, because the use of LEDs within static signs is still relatively new within the MUTCD, existing guidance is limited with respect to key design and operational factors such as LED color, spacing along the border, luminance, flash patterns, and frequency of use. This highlights the need for additional research to identify optimal and effective LED design characteristics.

MUTCD Specifications

Within the MUTCD, provisions related to roadway signs are addressed in Part 2. Most provisions related to the use of LED enhancements within static signs are located in Chapter 2A, which provides general criteria for signs, including size, placement, and other general provisions.

Within Chapter 2A, Section 2A.12 (LEDs Used for Conspicuity Enhancement on Standard Signs) establishes conditions under which LEDs may be used to enhance the conspicuity of static signs. The section clarifies that LEDs are intended to supplement, not replace, the sign legend and that their use does not convert a static sign into a changeable message sign.

When LEDs are used, the sign is still required to meet all applicable retroreflectivity and illumination requirements for nighttime viewing. The MUTCD places several constraints on LED application to preserve uniformity and driver comprehension, including limitations on where LEDs may be placed (e.g., within legends, symbols, or borders rather than sign backgrounds), restrictions on LED size and spacing, and requirements for appropriate color based on sign type.

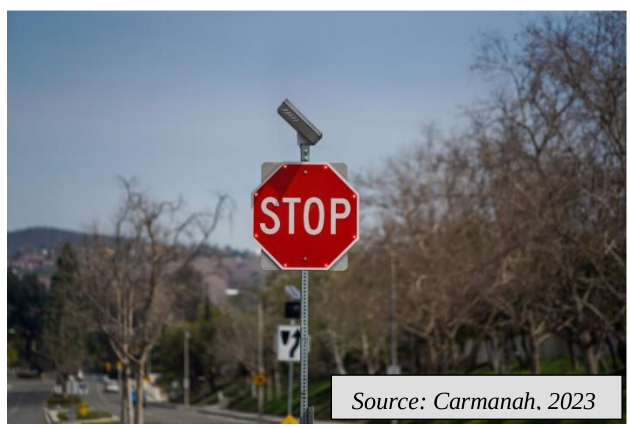
Provisions further specify that LEDs, if flashed, must flash simultaneously at a steady rate and that certain sign types (such as STOP and YIELD signs) require continuous operation without actuation.

Additional provisions specify that when used along the border, LEDs must be positioned along each edge and corner to ensure the sign shape is visible during nighttime conditions. For LEDs being used in the border of circular signs, the number of LEDs used must be enough to clearly form the appearance of a circle, to not be confused with a different shape.

Although the MUTCD establishes baseline standards for the use of LEDs within static signs, questions remain regarding the most effective application of this enhancement under varying conditions and sign types. Additional research could expand on the current MUTCD provisions by offering evidence-based recommendations to support decisions regarding when, where, and how to deploy LEDs within static signs.

State-of-Practice Review

This section summarizes the current state of practice regarding the use of LEDs within traffic signs. A number of state and local agencies across the United States utilize embedded LEDs within static signs to enhance visibility and conspicuity. Common applications include regulatory and warning signs such as STOP, WRONG WAY, DO NOT ENTER, YIELD, Pedestrian Crossing, STOP AHEAD, Speed Limit, and Chevron Alignment signs (U.S. DOT, 2009; Institute for Transportation, 2025; Carmanah Technologies, 2023; Institute of Transportation Engineers, 2015).



Source: Carmanah, 2023

Given the critical role these signs play in supporting safe driving behavior, supplementing them with LEDs is appropriate given their importance; failure to detect or respond to these signs could have severe consequences, including failure to stop at an intersection, wrong-way driving, pedestrian collisions, or roadway departures on curves. Enhancing the conspicuity of these signs through LED treatments is therefore intended to reduce the likelihood that drivers will miss essential information.

However, it is important that LEDs are used sparingly so drivers do not become accustomed to their presence and stop adhering to them (Institute of Transportation Engineers, 2015). Because of this, existing guidance and agency practice identify situations in which LEDs may be appropriate, including (U.S. DOT, 2009; Institute for Transportation, 2025; Minnesota DOT, 2017; FHWA, 2010):

- Locations with limited sight distance (horizontal curves, glare, etc.),
- Locations where drivers may fail to recognize an intersection,
- Intersections with a high crash rate history, and
- Intersections where a STOP sign may be unexpected.

There are currently no provisions in the MUTCD that provide a minimum or maximum value of brightness levels of LEDs embedded within static signs. One distributor of LED-embedded signs offers an optical light intensity of a minimum of 1,000,000 millicandela (mcd) during the daytime and is able to dim the daytime intensity between 10 and 100 percent for nighttime conditions (Carmanah, n.d.). Another distributor of LED-embedded signs offers a maximum of 5,200 lumens and their systems can automatically dim based on the amount of surrounding light in the environment (TAPCO, n.d.). Texas Department of Transportation (TxDOT) published specifications for LEDs embedded on curve warning signs and specified that the LEDs must output a minimum of 550,000 mcd during daytime peak and be able to automatically adjust the brightness to the surrounding environment (Texas DOT, 2024).

The cost of these systems and installation varies slightly. Pennsylvania installed a number of LED embedded signs around the state. The cost ranged from approximately $37,100 to $682,100, but all locations saw a positive benefit-cost ratio (U.S. DOT, 2023). Minnesota Department of Transportation (MnDOT) and North Dakota DOT reported a minimum cost per intersection between $2,000 and $3,000 and a maximum cost of $6,000, which included two LED-enhanced STOP signs and solar charging equipment (Minnesota DOT, 2017; North Dakota DOT, 2017). MnDOT also published a report that compared the cost of a passive LED STOP sign system, $2,000, and an activated LED STOP sign system, $20,000 (Minnesota DOT, 2016).

Literature Review

This section reviews and summarizes research on the human factors considerations related to the use of LEDs within static signs. Because prior studies use overlapping or inconsistent terminology to describe how drivers interact with signs, key terms are clarified to establish a consistent framework for this review.

In this paper, a driver’s ability to detect a sign is described in terms of visibility and conspicuity. Visibility refers to how easily the sign can be seen, while *conspicuity* refers to how readily the sign attracts attention relative to its surrounding environment. A driver’s ability to comprehend a sign is based on both recognition and legibility, where *recognition* refers to correctly identifying the sign and *legibility* is how easily the sign’s text or symbols can be read. Finally, *compliance* refers to whether and how drivers modify their behavior after viewing the sign.

The literature reviewed in this section examines the extent to which LEDs influence each of these stages of driver interaction with static signs: detection (visibility and conspicuity), comprehension (recognition and legibility), and compliance. Literature was reviewed to see how LEDs impacted each of these factors.

Detection of Signs

In practice, traffic signs are meant to be both visible and conspicuous, meaning drivers can both see the sign and notice it quickly, regardless of the environment or conditions. LED enhancements can help achieve this; however, there are certain situations under which the visibility or conspicuity of LED-enhanced signs may be reduced. How visible or conspicuous a sign is can vary depending on the time of day or condition of the roadway, even for the same sign. For instance, LEDs within a static sign where there is an abundance of light from the sun may have limited impact on visibility as the sun can diminish their relative contrast (Bullough, 2017; Theiss et al., 2022). In comparison, LED enhancements tend to be more effective during lower lighting situations such as fog, rain, snow, or nighttime conditions, where additional luminance can improve sign detectability (Dulebenets et al., 2021).

However, differing lighting conditions may not necessarily produce the same results in achieving conspicuity. If a driver is on a rural road and sees a static sign with LEDs, there is a greater possibility that the sign will be visible and conspicuous since there are fewer competing background visuals. In contrast, if a driver was in a city with lots of lights, people, cars, and buildings, LEDs may be less effective, even if they improve visibility, due to increased visual clutter (Inman & Philips, 2013; McPhee et al., 2004; National Academies of Sciences, Engineering, and Medicine, 2024; Shoptaugh & Whitaker, 1984). Generally, the more complex or cluttered the roadway environment, the more difficult it becomes to extract information from signs (Lerner et al., 2003) and the time it takes to locate and respond to sign information increases (Shoptaugh & Whitaker, 1984).

There are a number of factors that impact the effectiveness of LED enhancements on conspicuity, two of which being brightness and flash characteristics. The brightness levels of the LEDs are one of the more impactful characteristics when it comes to visibility and conspicuity as it can help draw the driver's attention to the device (Bullough, 2017; Bullough et al., 2000; Fitzpatrick, Avelar, & Robertson, 2015; Freyssinier et al., 2006). However, excessive brightness can have negative impacts, including visual discomfort, glare, and reduced ability to view other crucial roadway elements (Chrysler et al., 2017; Freyssinier et al., 2006; Fitzpatrick, Avelar, Potts, et al., 2015; Fitzpatrick et al., 2011; Sunkari & Institute, 2014). A study on LED-enhanced STOP signs found that that signs were most detected on the lowest brightness setting during nighttime conditions and the highest brightness setting during daytime conditions (Fitzpatrick et al., 2011). This finding suggests that LED brightness does not uniformly improve sign visibility or conspicuity across all lighting conditions.

Source: Fitzpatrick et al., 2015

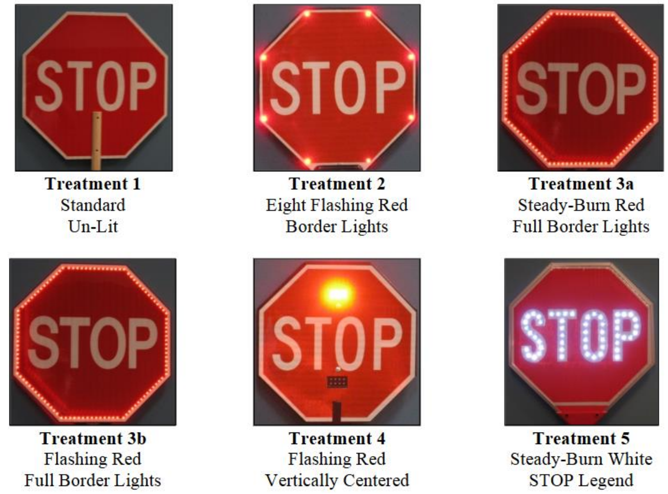
Flash patterns of the LEDs can also impact the visibility and conspicuity of the sign. Several studies have reported that flashing LEDs increased the sign's visibility and conspicuity compared to steady LEDs (Bullough, 2017; Fitzpatrick, Avelar, & Robertson, 2015). A study conducted by Texas Transportation Institute (TTI) evaluated various flash patterns by having participants view simulated beacons with five different flash patterns (Hawkins & Young, 2010). There were no significant findings across the different flash patterns, making it difficult for the researchers to recommend one flash pattern over another for implementation within static signs.

While LEDs can be a useful tool for increasing conspicuity and visibility, overusing them can lead to a decrease in effectiveness as people may stop paying as much attention to them (Institute of Transportation Engineers, 2015; Fitzpatrick et al., 2011; Forbes, 2011). This highlights the importance for the MUTCD to provide guidance on what situations warrant LED enhancements to avoid their overuse.

Comprehension of Signs

The ability to detect a sign and notice it with sufficient time to respond is important; however, detection alone is insufficient if drivers cannot recognize key characteristics of the sign, read its information, or comprehend its meaning. Recognition and legibility are therefore key factors that must be established regardless of any improvements in visibility or conspicuity provided by LED enhancements.

TxDOT conducted a laboratory study evaluating the impact of LEDs on recognition of a sign's shape, color, or type (Fitzpatrick et al., 2011). The study compared a number of different signs, including STOP (R1-1), YIELD (R1-2), PEDESTRIAN CROSSING (W11-2), Do Not Enter symbol (variation of an MUTCD sign), SPEED LIMIT (R2-1), Intersection Ahead (W2-1), Two-Direction Large Arrow (W1-7), and a circular STOP sign. The signs were tested with different LED configurations, colors, flash rates, and flash patterns. Overall, the study found that the inclusion of embedded LEDs decreased sign recognition time. During the lab portion of the study, participants perceived signs with LEDs enhancements as smaller than the standard unlit signs. When comparing the impact of different LED colors, seven LED arrangements were used on STOP signs. The seven variations included an un-lit, eight red dots in the border, 8 white bars flashing simultaneously in the border, 8 white bars with 4 bars flashing alternatively in the border, 8 red bars flashing simultaneously in the border, 8 red bars with 4 bars flashing alternatively in the border, and 4 red dots in the background of the sign. The results showed that the alternating flashing bars had the worse color recognition and the red simultaneous flashing bars had the best color recognition. For sign recognition, simultaneous flashing performed better an alternating flashing and red bars performed better than white bars. The researchers concluded that LEDs embedded in the border of signs can help with recognition, but as shown in the laboratory study, at greater distances, the LEDs have a greater potential to distort the shape of a sign. The research also found that using LED colors that match the sign background, such as red LEDs for STOP signs, can help distinguish the sign type.



Source: Finley et al., 2012

TTI performed a study to evaluate the impact of LED configuration and color on the recognition of STOP paddles (Finley et al., 2012). The configurations tested included a standard un-lit sign, eight flashing red LEDs embedded in the corner, steady red LEDs around the full border, flashing red LEDs around the full border, vertically centered flashing red LEDs, and steady white LEDs within the sign legend. The findings showed that the vertically centered flashing red LEDs and the steady white LEDs within the legend had a negative impact on driver's recognition of the sign compared to the un-lit paddle. In a post-task assessment, participants indicated that the vertical flashing lights were blinding and distracting, and the steady white LEDs made it more difficult to distinguish the red background color on the paddle. The study also found that none of the light configurations impacted the driver's ability to recognize the sign shape compared to the un-lit paddle, but the three red LED configurations along the border of the sign showed further recognition distances. Researchers suggested that this may be due to the over-glow of the white LEDs, making it more difficult to see the background color or shape.

The same TTI study also evaluated the legibility of the word "STOP" using the same LED colors and configurations (Finley et al., 2012). The results showed that the embedded LEDs did not impact the driver's ability to read the STOP legend of the sign compared to the un-lit paddle. For the paddle with the white LEDs within the legend, the legibility distance was further in the evening than during the day, and the legibility distance was further in the evening for this treatment compared to the flashing red LED borders or the vertical red LEDs. However, the post-task assessment indicated that participants found both the vertical red LEDs and the white LEDs within the legend difficult to read.

Another TTI study evaluated the legibility of WRONG WAY signs with different treatments (Finley, et al., 2014). The study was conducted on a closed course during nighttime conditions, and participants were impaired by alcohol. They were asked to indicate when they could read the legends of different signs placed along the roadway. The results showed that the legend of WRONG WAY signs with flashing red LEDs around the border were more difficult for the participant to read compared to other treatments. However, researchers indicated that additional research is needed to determine the optimal brightness of LEDs during different conditions that increase conspicuity without compromising legibility.

Recognizing color and shape can be extremely useful for signs such as STOP and YIELD, as those signs have a unique color and shape associated with them, so identifying that alone can provide drivers with clues to what to expect coming up. However, for signs such as warning signs that all have the same shape and color, being able to read the information on the sign is extremely important.

Compliance with Signs

The ultimate goal of enhanced conspicuity treatments is to influence driver behavior in a manner that improves roadway safety. While improving a driver's ability to see and detect a sign is a necessary first step, increased visibility alone does not guarantee that drivers will modify their behavior or comply with the sign's message (Katz et al., 2022; Theiss et al., 2022). Enhanced conspicuity is generally intended to draw drivers' attention to critical signs and, in doing so, increase the likelihood of appropriate behavioral response. All studies reviewed in this section were field studies.

Studies consistently demonstrate that enhanced conspicuity may increase compliance. MnDOT reported a 41.5 percent reduction in angle crashes after replacing a standard STOP sign with a flashing LED STOP sign (Davis et al., 2014). Another analysis conducted by MnDOT found that a flashing STOP sign that activated when a vehicle passed a STOP AHEAD sign, reduced approach speeds, increased stop duration, and eliminated rolling stops when another vehicle was in the intersection (Kwon & Ismail, 2014). Other studies similarly observed increases in the proportion of vehicles coming to a complete stop when there is an LED-enhanced STOP sign (Davis et al., 2014; Foomani et al., 2015; Gates et al., 2004; Van Houten & Retting, 2001), with some studies noting greater compliance during nighttime conditions (Arnold & Lantz, 2007; Li et al., 2020).

LED enhancements have also been associated with improved compliance for other regulatory signs. One study found a significant reduction in vehicle speeds approaching a railroad crossing after embedding LEDs within a Grade Crossing Crossbuck and DO NOT STOP ON TRACKS signs (Hellman & Lamplugh, 2016). Another study observed a decrease in the number of vehicles stopping within the grade crossing after embedding LEDs within the border of a DO NOT STOP ON TRACKS sign (Hellman, 2020).

Source: Hellman & Lamplugh, 2016

Findings for warning signs were less consistent. Warning signs are intended to alert drivers to upcoming conditions rather than mandate a specific action at the sign location, and compliance is often assessed indirectly through measures such as speed or yielding behavior. Several studies found increased driver yielding at pedestrian (W11-2), school (S1-1), and trail crossing (W11-15) warning signs when enhanced with LEDs (Ellis & Tremblay, 2014; Fitzpatrick et al., 2023). However, one study found no significant change in average vehicle speeds before and after the installation of a BE PREPARED TO STOP (W3-4) sign with LEDs within the border (Theiss et al., 2022).

Importantly, the absence of behavioral changes does not necessarily indicate that LED enhancements were ineffective. In some cases, baseline speeds or compliance rates at the study sites may have already been within acceptable ranges, limiting the potential for measurable improvements. Additionally, for warning signs in particular, it may not be reasonable to expect a consistent or immediate change in driver behavior, especially when the condition being warned of does not require a definitive response or when drivers are already behaving appropriately. The effectiveness of LED enhancements on compliance is likely context-dependent and influenced by both baseline conditions and the intent of the sign.

Conclusion

The selective integration of LEDs within static traffic signs represents an important advancement in enhancing road safety and communication where increased conspicuity it necessary. This review outlined real-world applications of LED-embedded signs, existing research on these devices, and current provisions on the use of LEDs within static signs. Together, the state of practice review and literature review highlight the continued technological advancement and the continued commitment to improving roadway safety through targeted conspicuity treatments.

This review highlighted research pertaining to the impacts of LEDs on the visibility, conspicuity, recognition, legibility, and compliance of roadway signs. While many studies demonstrate that LEDs can enhance visibility and conspicuity, the findings also indicate potential tradeoffs that agencies must consider when implementing these treatments. For example, some research showed that the inclusion of LEDs can obscure key sign characteristics, such as sign shape, or introduce excessive glare that can negatively impact legibility. These findings emphasize the importance of carefully balancing the attention-grabbing features with the need to preserve the essential visual information integral to sign comprehension and roadway safety.

Many field studies reported seeing an improvement in driver compliance following the installation of LED-embedded signs, particularly for STOP signs and selected warning signs. However, the magnitude and consistency of these behavioral changes varied by sign type, roadway context, baseline conditions, and LED configuration, and not all studies observed measurable improvements in compliance. These findings suggest that the effectiveness of LED enhancements depends on appropriate application and design.

As LED technology continues to evolve, ongoing research will be essential to refine best practices and inform future guidance. Addressing remaining gaps in knowledge will help inform appropriate deployment of LED-enhanced signs in a manner that increases safety, supports human factors principles, and meets the needs of all road users.

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