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RESEARCH ON TRAFFIC SIGN RETROREFLECTIVE SHEETING PERFORMANCE: A SYNTHESIS OF PRACTICE

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Traffic signs play an essential role in defining the safety and efficiency of the roadway environment. Signs use retroreflective sheeting to make them visible to drivers at night. There are many different types of sheeting, and practitioners need information to select the proper sheeting for a specific application. This document summarizes many of the issues involved in making decisions by summarizing prior research on retroreflective sheeting and related topics. The summaries address sheeting research in nine areas: basic retroreflectivity science; retroreflectivity materials, specifications, and measurement; sign performance; sign degradation; minimum retroreflectivity; field measurement of sign retroreflectivity; economic benefits; fluorescent materials; and safety. The summaries in each area describe key findings from previous research. More detailed information on each study is provided in an appendix document. The information gleaned from the research summaries serves as the basis for a series of recommendations on the use of retroreflective sign sheeting. Although these recommendations do not consider the impact of cost on sign sheeting selection, they do address sheeting selection based on roadway environment. The recommendations include using the highest grade of sheeting an agency can justify in urban environments where there is significant demand for drivers' attention and competing light sources at night. A higher grade of sheeting is also recommended in complex suburban environments. Type IV sheeting is recommended in low-volume rural environments for white and nonfluorescent yellow signs.

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16. Abstract (Limit: 250 words)

Sign retroreflectivity is an important characteristic of traffic signs, and it is a critical factor in defining the effectiveness of signs in a nighttime environment. This synthesis summarizes previous research on various aspects of sign sheeting retroreflectivity in nine areas: basic retroreflectivity science; retroreflectivity materials, specifications, and measurement; sign performance; sign degradation, minimum retroreflectivity; field measurement of sign retroreflectivity; economic benefits; fluorescent materials; and safety. The synthesis of previous research serves as the basis for recommendations for selecting sign sheeting based on sheeting grade and roadway environment.

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The purpose of this TRS is to serve as a synthesis of pertinent completed research to be used for further study and evaluation by MnDOT. This TRS does not represent the conclusions of either the authors or MnDOT.

Introduction

Traffic signs play an essential role in defining the safety and efficiency of the roadway environment. For roads that are open in both daytime and nighttime conditions, the *Minnesota Manual on Uniform Traffic Control Devices* (MnMUTCD) (1) requires signs to be retroreflective or illuminated to show the same color both day and night. Because illuminating signs is a more expensive method of providing nighttime visibility, the majority of signs use retroreflective sign sheeting to make signs visible to drivers. Retroreflective sheeting uses various types of optics to reflect light from vehicle headlamps back toward the driver, making the sign visible at a distance.

Over the years, the number of options available for providing sign retroreflectivity has grown. The practitioner must decide between type of optic, grade of sheeting, and manufacturer. When combined with the fact that most traffic engineers do not have a detailed knowledge of retroreflectivity science, choosing between the options can be daunting. This document summarizes many of the issues involved in making decisions on retroreflective sheeting by summarizing prior research on retroreflective sheeting and related topics.

When first used, retroreflective materials were limited in choices and the practitioner simply made a decision to use a retroreflective material. The earliest retroreflective signs were simply glass beads dropped on wet paint, which evolved into exposed bead sheeting. Then sheeting evolved into enclosed bead sheeting, which we now refer to as engineering grade, where the beads are embedded (or enclosed) in a plastic coating. Increasing the bead density and quality of enclosed lens beaded sheeting led to super engineer grade. These two products were generally available through the 1960s and 1970s. In the 1970s, encapsulated bead sheeting became widely available. This type of material, also known as high-intensity sheeting, has an air space between the beads and the surface coat. Encapsulated bead sheeting represented a higher level of performance for retroreflective materials through the 1970s and 1980s. In the 1980s, microprismatic sheeting became available, representing an even higher level of performance. Microprismatic sheeting eliminates the use of beads and relies on three smooth surfaces aligned at right angles (or nearly so) to one other. By modifying the alignment angles and prism orientation, the manufacturer can adjust the direction in which light is reflected by the sheeting. Microprismatic sheeting currently represents the highest level of sheeting performance. Many U.S. manufacturers have discontinued offering beaded sheeting products, in part due to environmental reasons associated with the manufacturing of this type of sheeting.

The next chapter summarizes some of the major research results related to retroreflective sheeting for the following topics:

- Basic retroreflectivity science
- Retroreflectivity materials, specifications, and measurement
- Sign performance
- Sign degradation
- Minimum retroreflectivity
- Field measurement of sign retroreflectivity
- Economic benefits
- Fluorescent materials
- Safety

The chapter after that provides recommendations based on these research findings, combined with the author's expertise in the field for selecting sign sheeting for various applications.

More detailed summaries of the research studies cited in the report, plus summaries of additional studies not cited in the summary chapter, are provided in the appendices. The summary for each research report or paper addresses the following topics:

- Title
- Source
- Author(s)
- Organization
- Year
- Sponsor
- Type of study
- Focus of study
- Study procedures
- Sample size
- General findings
- Takeaway message

Literature Review Process

Research studies have been evaluating the impacts of retroreflective materials for decades. The chapter provides an introduction to retroreflectivity science and retroreflective sheeting, then summarizes some of the key research findings associated with retroreflective sheeting.

Basic Retroreflectivity Science

Before selecting materials, it is important to understand how they work. The following content was prepared by the author for an FHWA report (2) and is adapted from that document. It provides a brief introduction to sign retroreflectivity science.

Retroreflectivity is a type of reflection that directs light back toward the source from which it came. If an observer is located close to the light source (such as a driver located behind a vehicle's headlights), the retroreflective target appears brighter than a non-retroreflective target. Retroreflectorization of signs is accomplished through the use of sheeting that contains beads or microprismatic mirror elements. The beads or prisms return illumination from a headlamp back towards a driver. Sign retroreflectivity is represented by the coefficient of retroreflection (R_A) and the unit of measure is candela per lux per meter squared ($cd/lux/m^2$). Retroreflectivity however, is a material property and is only one element that defines the luminance (the apparent "brightness") of a sign. The luminance of a sign depends upon multiple factors, including:

- the amount of light reaching the sign,
- the retroreflectivity of the sign (which is influenced by the condition of the sheeting, the presence of frost or dew on the face of the sheeting, and the orientation of the sign relative to the vehicle),
- the relative position of the headlamps, sign, and driver (collectively referred to as the viewing geometry), and
- other factors (such as atmospheric transmissivity (influenced by conditions such as rain, fog, and snow) and windshield transmissivity.

The apparent luminance of a sign is also affected by the age of the driver, as older drivers generally need a higher luminance for an object to appear as bright as it does to a younger driver.

The viewing geometry is defined by various angles between the headlamps, sign, and driver. There are several methods used to measure the viewing geometry and most of them are based on defining four measurement angles. The most common measurement systems (angle systems) are the application system, the intrinsic system, and the CIE goniometer system. The application system is the one that makes the most sense from a driving perspective. It is illustrated in Figure 1 and is based on the following angles:

- Observation (α)
- Entrance (β)
- Rotational (ε)
- Orientation (ω)

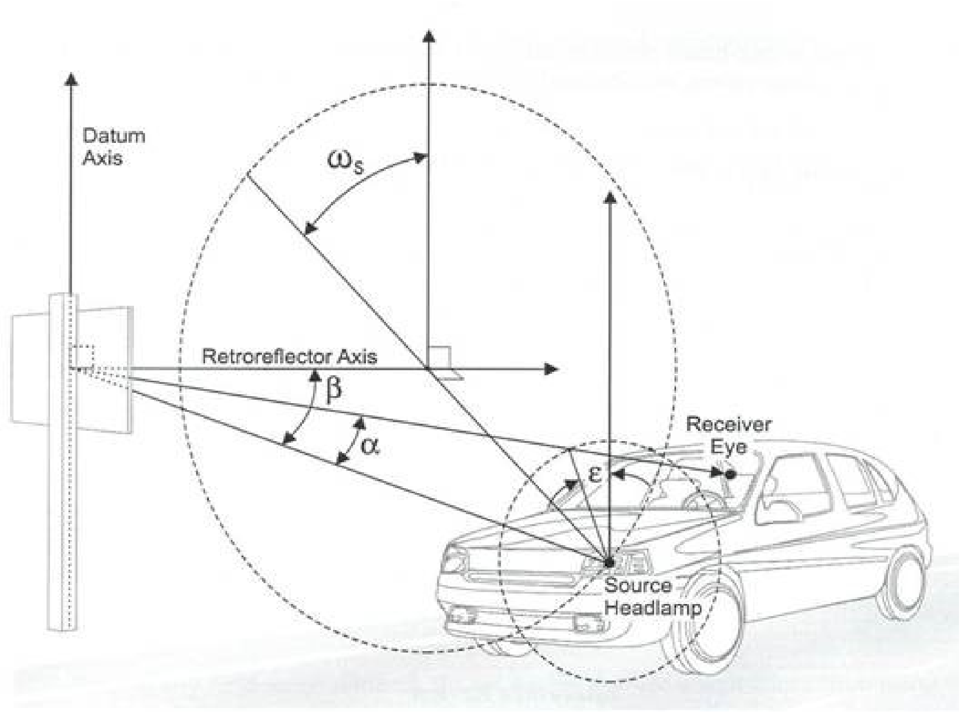

Figure 1. Application System of Retroreflectivity Angles (Source: CIE. Guide to the Properties and Uses of Retroreflectors at Night. CIE Publication 54.2. Vienna. Central Bureau of the CIE, 1987)

Of these angles, the ones with the greatest impact are the entrance angle and observation angle. These are the two angles that are measured when assessing whether a sign meets the minimum retroreflectivity criteria (discussed later). The observation angle is the angle between the light source (a headlamp) and the observer (a driver). The entrance angle is the angle between the light source (a headlamp on a vehicle) and the perpendicular to the target (a sign). Figure 2 and Figure 3 illustrate the concept of observation and entrance angles for measurement and real-world situations. In the typical roadway scenario, there are different entrance and observation angles for each headlamp on the vehicle. For viewing geometries that are the most common in the roadway environment, the observation angle is the more significant of the two angles for sign retroreflectivity.

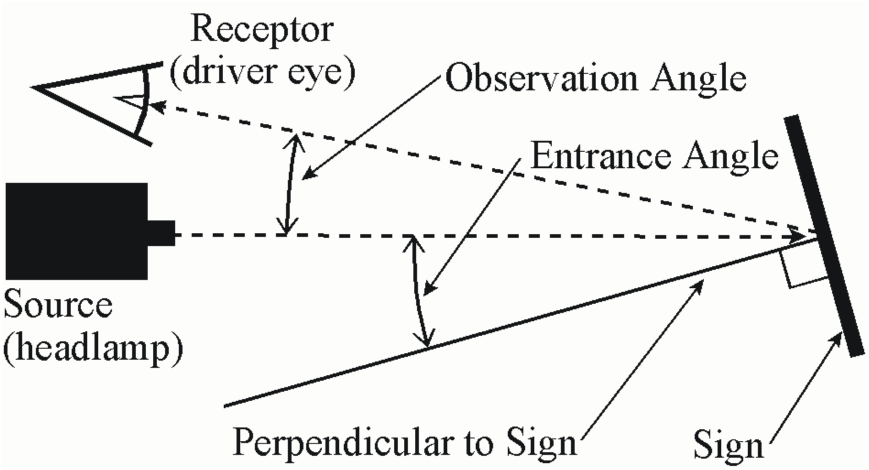

Figure 2. Entrance and Observation Angles for Laboratory Measurement (Source: Ref (2))

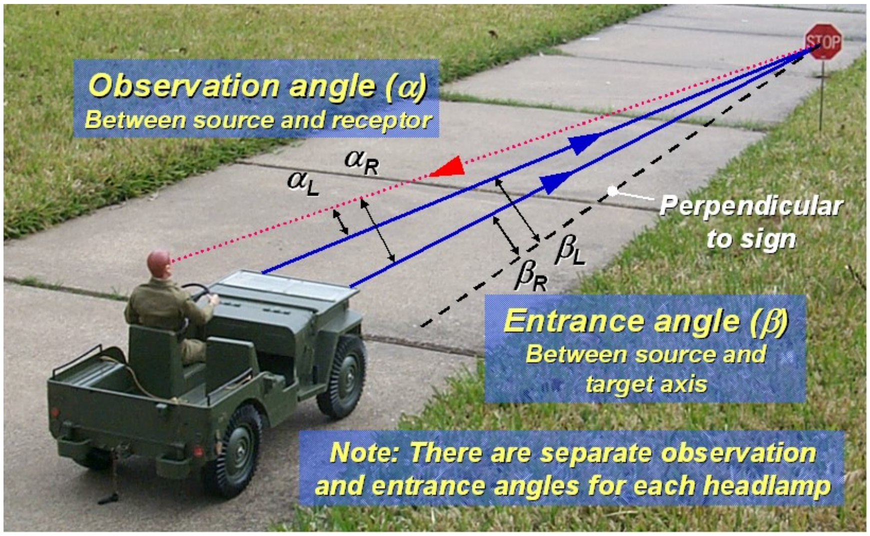

Figure 3. Entrance and Observation Angles in Real-World Conditions (Source: Ref (2))

The retroreflectivity level of a sign changes as the angles change. A sign that has a retroreflectivity level of 100 cd/lux/m2 at one set of measurement angles will have a different retroreflectivity level at a different set of measurement angles. Figure 4 illustrates how the retroreflectivity of a Type III (high intensity) material changes as a function of the entrance and observation angle. Therefore, retroreflectivity is often defined by standard measurement angles, which are discussed in the next section.

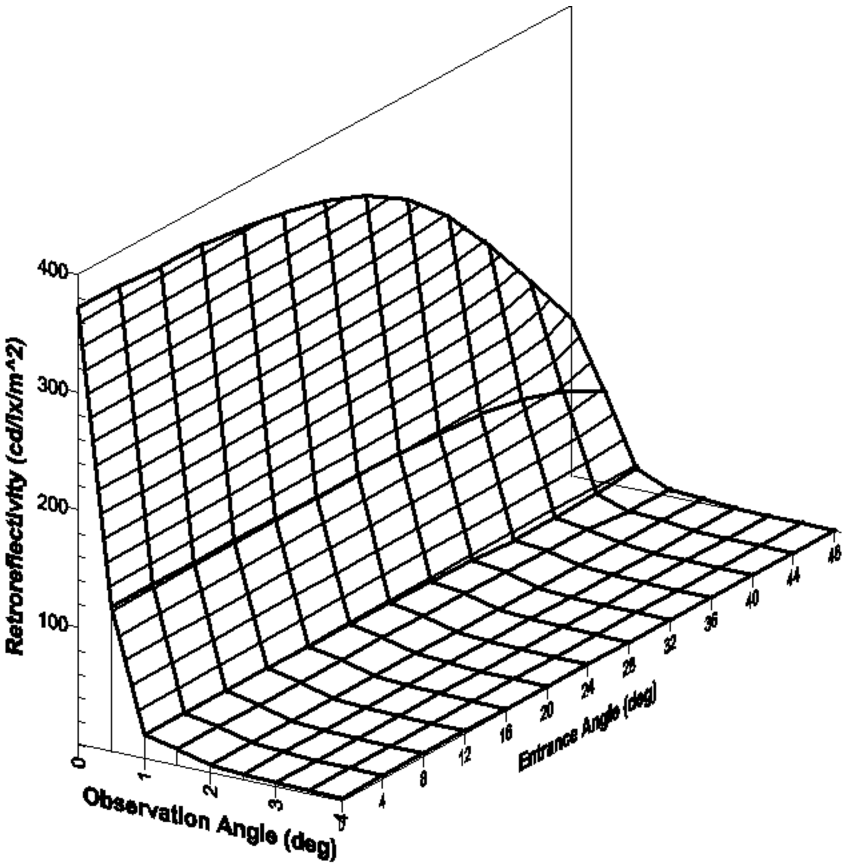

Figure 4. Retroreflectivity Variability Based on Measurement Geometry (Source: Ref (2))

Retroreflectivity Materials, Specifications, and Measurement

As mentioned in the previous section, sign retroreflectivity is measured as a function of various angles, which vary depending upon the angle system being used. Individual specifications establish the measurement angles and standard values for those angles.

The most common of the sign sheeting specifications is ASTM D4956 (3). This specification defines the different type of sheeting materials for signing applications and establishes retroreflectivity performance criteria for accepting new materials. The sheeting types defined in this specification include:

- Type I: A retroreflective sheeting referred to as "engineering grade" that is typically an enclosed lens glass-bead retroreflective material or a microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type II: A retroreflective sheeting referred to as "super engineer grade" that is typically an enclosed lens glass-bead retroreflective material or a microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type III: A retroreflective sheeting referred to as "high-intensity" that is typically manufactured as an encapsulated glass-bead retroreflective material or as a microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.

- Type IV: A retroreflective sheeting referred to as “high-intensity” that is typically an unmetalized microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type V: A retroreflective sheeting referred to as “super high-intensity” that is typically a metalized microprismatic retroreflective element material. This sheeting is typically used for delineators.
- Type VI: An elastomeric retroreflective sheeting without adhesive. This sheeting is typically a vinyl microprismatic retroreflective material. Applications include orange temporary roll-up warning signs, traffic cone collars, and post bands.
- Type VII: The use of a designation as Type VII has been discontinued.
- Type VIII: A retroreflective sheeting typically manufactured as an unmetalized cube corner microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type IX: A retroreflective sheeting typically manufactured as an unmetalized cube corner microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.
- Type X: The use of a designation as Type X has been discontinued.
- Type XI: A retroreflective sheeting typically manufactured as an unmetalized cube corner microprismatic retroreflective element material. Applications for this material include permanent highway signing, construction zone devices, and delineators.

ASTM D4956 establishes retroreflectivity performance criteria based on the observation and entrance angles as indicated below for each type and color of sheeting. The combinations of these angles used to define sign performance (i.e., α=0.2°, β=-4° is the most common for field measurements and used for defining in-service minimum retroreflectivity criteria) for material testing are not intended to the geometries associated with a vehicle on a typical road casting light on a roadside sign. In comparison to the standard measurement geometries, the real-world viewing geometries for a sign that has a centroid 14 ft to the right of the edge line and 9 ft above the road are shown in Table 1. As can be seen from this table, the typical geometry used for minimum retroreflectivity in the field (α=0.2°, β=-4° for minimum retroreflectivity) does not represent an actual location on the roadway with respect to a sign.

- Types I, II, III, IV, V, VI, VIII:
    - Observation angles: 0.2°, 0.5°
    - Entrance angles: -4°, +30°
- Types IX, XI:
    - Observation angles: 0.2°, 0.5°, 1.0°
    - Entrance angles: -4°, +30°

Table 1. Viewing Geometry for Real-World Conditions

Distance from vehicle to sign (ft)	Observation Angles (degrees)		Entrance Angles (degrees)	
	Left headlamp	Right headlamp	Left headlamp	Right headlamp
100	1.757085	13.17684	1.984105	10.28576
200	0.754171	6.676697	1.146973	5.184651
300	0.472075	4.462345	0.801096	3.461681
400	0.342299	3.34972	0.614646	2.597643
500	0.26816	2.680876	0.498379	2.078627

ASTM D4956 also contains criteria for measuring the color of retroreflective sign sheeting. Color measurements are based on the daytime luminance factor (Y) and chromaticity coordinates (x, y).

AASHTO has developed its own specification for sign sheeting (4) which defines four types of sheeting materials as indicated below. The measurement angles in the AASHTO specification include the 1.0° observation angle for all material types.

- Type A: Retroreflective sheeting materials meeting Type A are typically constructed of encapsulated microscopic glass bead lens construction.
- Type B: Retroreflective sheeting materials meeting Type B are typically constructed of unmetallized microprismatic optics. These triangular microprismatic materials do not have a significant 1-degree observation angle performance.
- Type C: Retroreflective sheeting materials meeting Type C are typically constructed of unmetallized microprismatic optics. These triangular microprismatic materials have a significant 1-degree observation angle performance.
- Type D: Retroreflective sheeting materials meeting Type D are typically constructed of unmetallized microprismatic optics. These materials have 0.5- and 1.0-degree observation angle performance approximately two times greater than Type C materials.

Most states rely upon either the ASTM or AASHTO sheeting specifications, but a few states have developed their own. MnDOT approach is to use an Approved/Qualified Products List (5) that limits retroreflective sheeting materials to specific products. The products currently on the list correspond to ASTM Types III/IV, IX, and XI. Illustrate the luminance difference provided by a typical Type III, VIII, IX, and XI white sheeting product in a common modern roadway environment. All of these products display a maximum luminance around 800 feet, although there are some significant differences in the magnitude of the provided luminance. The luminance decreases as the vehicle approaches the sign

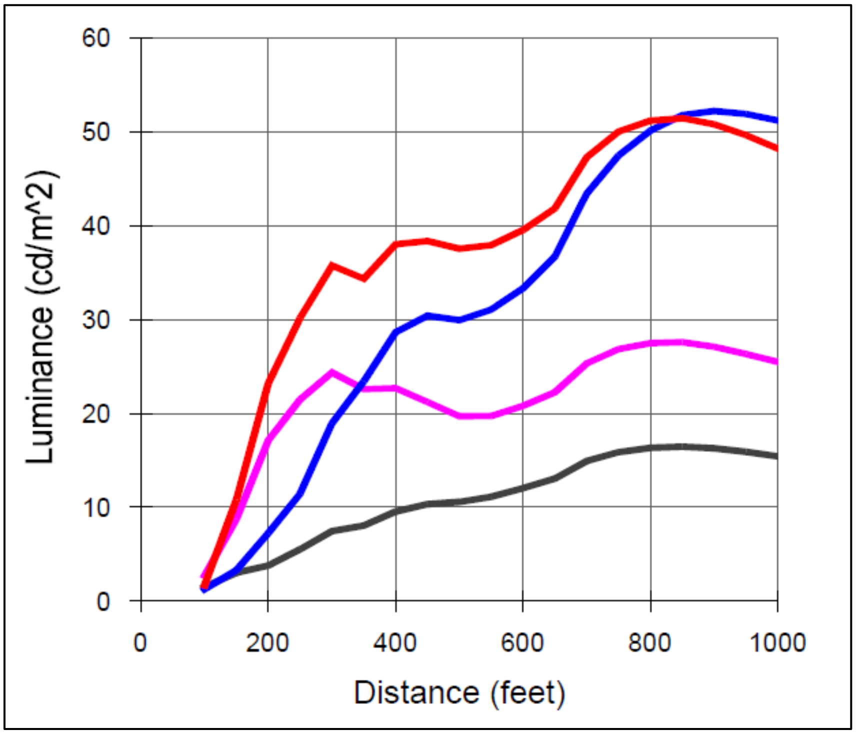

Figure 5. Comparison of Luminance Provided by Different Sheeting Grades

Sign Performance

Having established a basic foundation for retroreflectivity science and how retroreflectivity is measured and defined in specifications, it is appropriate to address how researchers have measured sign visual performance in various studies. There are several measures by which the visibility of a sign can be measured. These include luminance (brightness), legibility (ability to read the legend), and conspicuity (ability to identify the sign presence). Sign color and retroreflectivity are important factors in these measures. The following provide brief summaries of research reports or papers on sign performance identified in the early stages of this project. Summaries of the individual reports and papers are in Appendix A.

For sheeting material selection, a study by Zwahlen et al. (6) indicated that drivers typically preferred Type VII or Type XI legends on Type III backgrounds for legibility, readability, conspicuity, and appearance. Type XI legend showed preference however due to the minimal glare it produced in unlighted conditions as compared to Type VII. This information is useful for DOT's when determining the proper sign sheeting materials to use for street signs as well as overhead guide signs as legibility needs are to be considered for all users on the roads in order to promote safety and provide driver with the information to make decisions. However, in a study by Carlson (7) in determining if traffic signs could be too bright for low volume roads, it was indicated that the use of high-beams on signs utilizing Type XI legends showed a smaller legibility distance as compared to Type III, indicating that in remote areas, the use of high intensity sheeting may be inappropriate.

For warning signs, a study by Eccles and Hummer (8) indicated that fluorescent yellow warning signs are able to provide a cost effective measure in preventing collisions due to roadway hazards. A study later done by Gates et al. (9) indicated that the placement of fluorescent yellow chevrons greatly reduced the potential of crashes on curves when lane encroachment was used as a measure of effectiveness.

As there are many factors that can contribute to a sign not providing the adequate legibility such as being dirty or aged from weathering, a study by Hildebrand (10) showed that dew and frost can also impact the retroreflectivity of a sign. In areas which are expected to have a substantial amount of dew or frost annually, it is recommended to use to a higher grade sign sheeting material to offset the effects while still provided adequate reflectivity without the potential of glare when these factors aren't in place.

The performance of overhead signs is becoming more difficult as typical vehicle fleets are changing every year. In a study done by Carlson and Hawkins (11) regarding overhead guide sign legibility, it was determined that as the typical vehicle fleet begins to shift towards larger vehicles, overhead signs will require greater legibility in order to accommodate the reduced amount of illuminance from the headlamps reaching the sign. This luminance can be done using external lighting or using a high luminance sheeting type such as Type III or Type XI. For the use of external lighting, a study by Obeidat et al. (12) showed that induction lighting was the most cost-efficient lighting source followed by LED's. Using a cost efficient yet effective external lighting is important as these lights would consume a lot of energy which would be costly to the DOT if not properly selected.

One of the more interesting experiments involved the use of eye tracker data to determine the effects of background complexity and sign luminance on sign recognition and legibility. A study performed by Carlson et al. in 2009 (13) showed that many of the controlled roadway studies where no other vehicles were present and where there were no obstacles to be concerned about may be inaccurate in how drivers react to traffic signs. There was no correlation which could be developed for these controlled studies whereas in studies performed on an actual road, the driver is focused on not only sign detection, but also obstacles and other drivers on the road. Higher luminance signs also provide the driver with the ability to detect and acquire information quicker, resulting in a glance duration less than that of lower luminance signs.

Bible et al. (14) performed a simulator study regarding the luminance based on different types of sign sheeting material (VII,VIII, and IX) in different scenarios. It was observed that each had a unique benefit such as Type VII and VIII were better for long distances and perpendicular mount whereas Type IX is better for closer viewing distances. In larger entrance angles, such as observed by Brich's study when vehicles are further, the use of Type VII provides more luminance.

In a survey by Gerado W. Flintsch (15) in 1993 with the Arizona DOT, it was indicated that most states utilize Type III sign sheeting material for warning and regulatory signs with a mix of Type I and Type III for other signs such as guide signs. Sign minimum reflective requirements are commonly inferred to by FP-85, followed by AASSHTO, and ASTM (this is before the FHWA minimums were developed). Cleaning of signs is rare with the most common form of maintenance being replacement when necessary.

A cooperative study between the Illinois Center for Transportation and Texas A&M Transportation Institute (16) contributed to the development of the AASHTO sign sheeting specification (4). This study used test subject to provide subjective judgments on the performance of different grades of sheeting classified according to the AASHTO sheeting specification. The results indicate that:

- When AASHTO Class A was compared to AASHTO Class B, 96% of responses rated Class B as better.
- When AASHTO Class A was compared to AASHTO Class C, 86% of responses rated Class C as better.
- When AASHTO Class A was is compared to AASHTO Class D, 93% of responses rated Class D as better.
- When AASHTO Class B was compared to AASHTO Class C, 18% of responses rated Class C as better.
- When AASHTO Class B was compared to AASHTO Class D, 43% responses rated Class D as better.
- When AASHTO Class C was compared to AASHTO Class D, 52% responses rated Class D as better.

Sign Degradation

One of the challenges with meeting driver needs for traffic sign visibility is that retroreflective sign sheeting degrades over time. The amount of degradation can vary due to many different factors, including type of sheeting, age of sheeting, location/climate, direction of sun exposure, and altitude. Several research efforts have attempted to establish a reliable relationship for predicting the retroreflective performance of sheeting over time but none have been successful to date. The following provide brief summaries of research reports or papers on sign degradation identified in the early stages of this project. Summaries of the individual reports and papers are in Appendix B.

The aging of signs overtime has been shown to affect the performance in both color chromaticity and retroreflectivity. In a study performed by Brimley et. al, (17, 18) it was observed that white and green signs failed under retroreflectivity standards typically whereas orange, red, and yellow signs would fail first under chromaticity. The signs which failed chromaticity would in general fail prior to those which failed under retroreflectivity.

In a study performed by Boggs et. al, (19) it was observed that areas with higher elevations, higher temperatures, as well as rainfall showed greater sign damage. Areas which experience extreme climates would require greater frequency in sign replacement as well as maintenance as compared to others. One way to help with this issue would be to use a more durable sign sheeting material such as from Type I to Type III.

Warren D. Ketola (20) performed a study analyzing the validity of laboratory weathering studies of sign sheeting materials and found that there was great variability when compared to outdoor weathering as certain conditions can't be replicated such as extreme weather. This is deemed as one of the big reasons why many agencies have begun the shift towards outdoor weathering, although a longer process would produce more accurate results that would not over predict the life expectancy of sign sheeting based on the MUTCD standards for retroreflectivity.

Minimum Retroreflectivity

The retroreflectivity criteria in the ASTM and AASHTO sheeting specifications are intended to provide quality control for acceptance of new materials. They are not intended for establishing end-of-life criteria for traffic signs in the field. To address that need, the FHWA added minimum levels of retroreflectivity to the Manual on Uniform Traffic Control Devices (MUTCD) in 2007 to include criteria for defining end-of-life for selected traffic signs based on the retroreflectivity level. Those criteria remain in the current MnMUTCD (1) and are reproduced below in Table 2. This table in the MUTCD includes a listing of bold symbols signs and fine symbols signs.

Table 2. Minimum Maintained Retroreflectivity Levels[1]

Sign Color	Sheeting Type (ASTM D4956-04)				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VII, VIII, IX, X	
White on Green	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25	Overhead
	W*; G ≥ 7	W ≥ 120; G ≥ 15			Post-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			2
	Y*; O*	Y ≥ 75; O ≥ 75			3
White on Red	W ≥ 35; R ≥ 7				4
Black on White	W ≥ 50				--

Notes:

[1] The minimum maintained retroreflectivity levels shown in this table are in units of cd/lx/m^2 measured at an observation angle of 0.2° and an entrance angle of -4.0°.

[2] For text and fine symbol signs measuring at least 48 inches and for all sizes of bold symbol signs

[3] For text and fine symbol signs measuring less than 48 inches

[4] Minimum sign contrast ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity)

*This sheeting type shall not be used for this color for this application.

The minimum sign retroreflectivity levels in the MUTCD are based on research that was conducted over an extended period. Some of the key studies in this research effort are described below Summaries of the individual reports and papers are in Appendix C.

In 1993, a study performed by Paniati and Mace (21) for the minimum retroreflectivity requirements for traffic signs utilizing Computerized Analysis of Retroreflective Traffic Sign (CARTS) model. This study established the first general criteria for minimum sign retroreflectivity but was later found to have significant flaws such as not evaluating street signs and using a single headlamp, also known as cyclops modeling where the headlamp placement was more related to that of a motorcycle rather than a four-wheeled vehicle. Revisions for this issue were later done in 1998 by the developers of CARTS (22). Later studies done by Hawkins et al. (23, 24, 25) would further account for the short-comings of the CARTS model. These studies indicated that there were many factors such as roadway geometry, traffic volume, vehicle type, age, headlamp luminance, sheeting color and type all play a factor in determining the necessary minimum retroreflectivity required for drivers to acquire information from signing during nighttime. There is no correct answer for the minimum retroreflectivity for all signs types used on roadways as vehicle types are constantly changing, different environments in different areas, etc. The Carlson and Hawkins research efforts resulted in recommendations for minimum levels of retroreflectivity that were eventually incorporated into the MUTCD. Later research at TTI by Holick et al. (26) developed minimum retroreflectivity recommendations for blue and brown signs, which had not been addressed in the previous research, and which have not yet been added to the MUTCD.

Other research by Hawkins and Carlson (27) evaluated the ability of field personnel to conduct nighttime visual inspections as a method of implementing their recommendations for minimum sign retroreflectivity. The results indicated that the field personnel rejected more signs than would have been rejected based only on retroreflectivity measurements.

A study performed by Hulme et al. (28) did demonstrate that Type III signs distinguish this signing material as being more effective for providing minimum retroreflectivity standards as proposed by the FHWA for longer durations while being more cost effective. Nuber and Bullock (29) performed a study which indicated that the manufacturers of the signs provided a warranty period that did appear to be sufficient as a potential sign replacement program protocol as these warranty periods did show most signs met or exceeded the minimum retroreflectivity requirements of the FHWA standards.

Field Measurement of Sign Retroreflectivity

While sign sheeting standard specifications apply to acceptance of new sign sheeting, the MUTCD minimum retroreflectivity criteria described in the previous section represents field measurements of actual signs in the field. The goal of the field measurement activities for traffic signs is to identify the optimal time to replace existing traffic signs. Several research efforts have made actual retroreflectivity measurements of signs in the field and the significant ones are described below. Summaries of the individual reports and papers are in Appendix D.

One of the most comprehensive field evaluations of sign sheeting materials is conducted as part of the National Transportation Product Evaluation Program (NTPEP) (30) sponsored by AASHTO. In this program, sign sheeting samples are exposed on a outdoor test deck for a period of years. The program is conducted to help agencies evaluate producted for acceptance. However, the exposure period for sign sheeting is not long enough for the products to fail on the basis of the minimum retroreflectivity values. As a result, the NTPEP program results have limited value in predicting or evaluating the service life of traffic signs based on retroreflectivity.

A research effort by Clevenger et al. (31) conducted both field study of sign retroreflectivity and a survey of state replacement practices. The field study indicated that all but a small number of signs had retroreflectivity levels that were lower than the MUTCD criteria. Of those that did fail, most had been in the field for more than 15 years. The survey of states indicated that states utilize different approaches when it comes to sign replacement programs. Some of the methods include past experience and previously published research papers, life expectancy by the manufacturer, and life expectancy by the manufacturer with blanket replacement. Few indicated that they were actually measuring retroreflectivity in the field.

Sharma (32) evaluated sign sheeting retroreflectivity by measuring the initial retroreflectivity of 125 new sign samples (both with and without stone bruising) and the samples were placed on vertical racks facing south. Signs were measured for their retroreflectivity every 6 months after washing. Signs were studied for 10 years. Most of the engineer grade materials did not perform well over the 10 year period, which was not surprising as this type is generally assumed to have a service life of about 7 years. Some of the products in this evaluation were no longer available by the time the study concluded.

In a field study by Stephen C. Brich, (33) it was noted that construction and maintenance signs are often placed with no specific standards or specifications as set by DOT's. This poses major challenges in determining the required reflectivity for drivers to be able to detect and recognize the sign. Brich evaluated the position of signs relative to the roadway to determine the viewing angles that represent real-world viewing geometry. The results indicated that actual viewing geometries are significantly different from those used in acceptance specifications and for minimum retroreflectivity criteria.

Economic Benefits

There have been few efforts focused on the economic benefits of different types of retroreflective sheeting. The difficulty of establishing such a relationship is based on several factors, including: higher performing sheeting materials are more expensive, there are not good data on the types of materials in the field that allow an economic analysis of the costs and safety benefits, the prices of sheeting materials vary depending upon the product, purchasing agency, and quantity purchased. Only one research was identified and is described below. A summary of this study can be found in Appendix E.

A study done by McGee and Taori (34) in 1998 demonstrated that in general, local jurisdictions required more signs to be replaced than state jurisdictions in all sign categories based on minimum retroreflectivity. While most agencies already have a replacement schedule in place for worn or old signs, it was found in a safety study by Ripley in 2005 that the replacement of engineering grade signs with high intensity or diamond sheeting drastically reduced the number of crashes observed with a typical ten year benefit-cost ratio of 11.1:1 – 267:1. In general, signs which provide higher retroreflectivity, whether that be replacing old signs or using high luminance sheeting material would provide a benefit-cost ratio which could be justified by an agency as a reason for sign replacement.

Fluorescent Materials

Fluorescent sheeting materials started becoming a viable option for agencies in the early 1990s. Fluorescent sign materials provide enhanced luminance and conspicuity for drivers, especially during dawn and dusk periods, whereas this effect is reduced during nighttime hours. The impacts of fluorescent materials as identified in a few research studies are reported below. Summaries of the individual reports and papers are in Appendix F.

In one of the earliest studies of fluorescent signs, Burns et al. (35) conducted a controlled field study on sign detection, recognition, and color for orange, red, and white signs. The fluorescent materials generally outperformed the nonfluorescent materials, although daylight conditions deteriorated the advantages of the fluorescent materials. Fluorescent material was especially beneficial for recognition and color identification.

In another early evaluation of driver response to fluorescent signs, Zwahlen et al. (36) conducted a controlled field study where drivers identified sign color. He found that fluorescent colors generally provide the highest percentage of detection.

The technical report for a study by Brich (37) evaluated work zone sign positions in the field (also reported in (33)). The report stated that fluorescent signs remain a cost-efficient solution to providing drivers a conspicuous sign type to convey necessary information to prevent accidents on the roadway.

Hummer et al. (38) evaluated the impact of fluorescent signs on lane closures in work zones by comparing the results of fluorescent and standard color signs on driver behavior. He recommended that fluorescent sheeting material should be utilized in construction/work zones to protect those working in these areas, as observations indicated there were fewer traffic conflicts from speed changes, lane changes, and merges that would generally result in collisions and accidents in work zone areas. Hummer indicated that fluorescent signs provide drivers greater ability to recognize the signs in the daytime due to its improved conspicuity.

Burns et al. (39) also conducted another study on fluorescent yellow and yellow-green signs that included both laboratory and field evaluations on a controlled field study. The findings showed that the fluorescent signs have higher daytime luminance and that fluorescent signs generally provide greater visibility and detail for road users.

In a field study by Eccles that has been previously referenced (8), a field study of fluorescent signs found that fluorescent yellow signs demonstrated statistically better driver performance at sites that had fluorescent yellow signs in place. Examples of performance measures included centerline and edgeline encroachments, stop sign observance, brake light distance, conflicts, events, and speed.

Safety

One of the basic tenants of the MUTCD is that traffic signs, when used appropriately, improve the safety of the roadway environment. While many research studies have shown the value of traffic signs versus not having signs, few have addressed the safety impacts of retroreflective sheeting on safety, as measured through crashes. This studies identifies a few of those studies. Summaries of the individual reports and papers are in Appendix G.

In two studies performed by Vanasse Hangen Brustlin, Inc. (VHB), (40, 41) it was seen that an increased retroreflectivity reduced the number of crashes. For the study on Stop sign retroreflectivity (40), the study found that replacing Type I sheeting material stop signs with Type III and Type XI sheeting material showed statistically significant reduction in crash rates for low volume intersections as well as three-legged intersections, but no significant reduction in crash rates at night-time was found. For the curve delineation study (41), it was found that increased curve delineation greatly decreased the crash rate, especially during night-time hours. The safety study performed by Ripley (42) also found that increased retroreflective signing provides a benefit-cost ratio that shows the significance of higher retroreflective signing on crash reduction.

Recommendations for Sign Sheeting Practices

The findings from previous research efforts provide some insight into the complexities of selecting retroreflectivity sign sheeting. While there are no definitive rules for selecting sign sheeting, the following guidelines appear reasonable based on prior research and expert opinion.

- The cost of sign sheeting varies by manufacturer, material type, agency, and quantity purchased. This synthesis of prior research does not include identification of current sheeting costs. Therefore, costs are not included as a factor in the recommendations for selecting sign sheeting.
- Beaded materials (ASTM Types I, II, and III) are not practical options for state transportation agencies due to the products' limited availability and lower levels of performance.
- Currently available microprismatic materials include the ASTM types listed below. Current U.S. manufacturers of these products are listed as well.
  - Type IV (generally equivalent to a beaded Type III product)
    - 3M High-Intensity Prismatic Reflective Sheeting Series 3930
    - Avery-Dennison T-6500 High-Intensity Prismatic (HIP) Series
    - Nikkalite CRG 94000 Series Crystal Grade
    - ORAFOL ORALITE 5900 High-Intensity Prismatic Grade
  - Type VIII

    Nikkalite CRG 92000 Series Crystal Grade
    Avery-Dennison T-7500 MVP Series Microprismatic

  - Type IX
    - 3M VIP Reflective Sheeting Series 3990
  - Type XI
    - 3M Diamond Grade™ DG³ Reflective Sheeting Series 4090
    - Avery-Dennison OmniCube T-11500 Series
- Fluorescent materials are available only in microprismatic materials.
- The expected life of a microprismatic sign can generally be assumed to be 15 years or more based on retroreflectivity performance. In some locations, there is the potential for shorter life due to environmental conditions.
- There are no end-of-life criteria for the color of traffic signs. Limited research has shown that color may have more impact than retroreflectivity on end-of-service life. For white, yellow, and green microprismatic signs, the life of the color can generally be assumed to be 15 years or more if the color is a manufactured color (i.e., not screened).
- The expected life of the fluorescent materials is shorter than standard colors due to the loss of fluorescence that occurs at a more rapid rate than the loss in retroreflectivity. However, there are no in-service or end-of-life criteria for determining when to replace fluorescent signs. Although data on the life of fluorescent signs are limited due to the difficulties of measuring fluorescence, a life of 7-12 years may be appropriate. The warranty period for fluorescence may be the best indication of the minimum expected life of such signs.
- In temporary traffic control applications (TTC), fluorescent orange signs should be used due to the fact that the life of TTC signs is relatively short.
- In urban areas where there is significant need for drivers' attention and competing light sources at night, an agency should strive to use the highest grade of sheeting it can provide.
- In suburban areas where there may be isolated locations with significant visual complexities, an agency should strive to use the highest grade of sheeting it can provide at locations with high driver demand, such as intersections, interchanges, approaches thereto, and alignment changes requiring significant speed reductions.
- In low-volume rural areas (ADT of 5,000 vehicles per day or less), Type IV signs should be used for white signs and nonfluorescent yellow signs.
- In rural areas, the use of fluorescent signs should be limited to locations where additional emphasis is desirable, such as alignment changes with significant speed reductions.

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