Durable Fluorescent Materials for the Work Zone

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Construction work zones (CWZs) are a major cause of concern for highway and safety engineers. At any given time CWZs constitute only a small fraction of the total roadway miles. However, they are the site of an increasing number of roadway accidents each year. The traffic safety industry has attempted to respond to this problem by providing brighter retroreflective signing materials to increase the nighttime visibility of the CWZ. The equally important need for increased daytime visibility has prompted traffic engineers to experiment with fluorescent colors in the CWZ. Fluorescent colors have outstanding visibility under all daylight driving conditions. Even so, fluorescent colors have never achieved widespread acceptance in outdoor signing applications. The primary obstacle has been the very poor color stability of fluorescent signing materials. A typical fluorescent roadway sign has lost most, if not all, of its color within 1 year. Often it is only a matter of months or weeks. Recent developments have resulted in a redefinition of the contribution that fluorescent colors can make toward improving traffic safety. A fluorescent retroreflective sheeting with color durability similar to existing CWZ sheetings is now available. A field study was run to compare the visibility performance of this fluorescent retroreflective sheeting with that of conventional fluorescent films and ordinary retroreflective materials. The results of the study indicate that fluorescent retroreflective sheeting provides better daytime and nighttime visibility than do ordinary signing materials.

Safely navigating the national roadway system is becoming more difficult for the average driver. The increasing visual complexity of the driving environment, increasing traffic loads at all hours, and the seemingly endless roadway reconstruction and maintenance activities are putting a higher sensory load on the driver. The motorist's task of screening out the important driving information is becoming increasingly complex. Roadway traffic control devices (signs, etc.) are the primary communication link between the driving environment and the driver. They must effectively provide the essential regulatory and safety information.

Modern traffic control devices convey information using a redundant coding system of symbols, legends, shapes, and colors, where each attribute has an assigned meaning. By combining attributes the driver is presented with a number of visual prompts, all of which convey and reinforce the message. One example is the construction work zone (CWZ) warning sign used in the United States. The orange color (construction zone warning), diamond shape (warning roadway hazard), and legend "LANE ENDS 1500 FEET" (warning) each alert the driver to a possible hazard ahead (*1*). Devices that effectively communicate with the motorist share four basic characteristics: they are conspicuous and legible and the message is easily understood and credible (*2*). Foremost among the requirements is conspicuity. When a sign or other device is not seen because it does not successfully compete for the driver's attention, it makes no difference what the message is. The transportation safety industry has four basic control mechanisms for adjusting the conspicuity of traffic control devices: size, shape, color, and retroreflective brightness, for nighttime visibility. The first attribute identified, both night and day, is color (*3–5*).

Jenkins and Cole (*2*) and Cole and Hughes (*6*) have defined two levels of conspicuity with respect to traffic control devices: (*a*) search conspicuity (the ability "to be quickly and readily located by search") and (*b*) attention conspicuity (the ability "to attract attention when the driver is unaware of its likely occurrence").

Search conspicuity is required of guide signs and informational signs. CWZ, pedestrian crossing, and school zone signs need the higher-level attention conspicuity to perform their function. It is important that these types of warning signs maintain a high level of conspicuity at all times.

As the need for higher-visibility traffic control devices has evolved, researchers have responded with improved materials and new technologies. A review of the literature indicates that the majority of that work has focused on nighttime visibility (retroreflectivity). Improving visibility for the night driver is critically important. National accident statistics indicate that 55 percent of the fatalities occur at night, when only one-third of the drivers are on the road (*7,8*). However, improving daytime conspicuity is also very important. The vast majority of all traffic accidents, including the remaining 45 percent of traffic fatalities, occur during daylight, when retroreflective performance plays no role. Of particular importance is the need to improve the daytime visibility of traffic control devices under low light (dawn and dusk) and adverse weather conditions.

A number of visibility studies conducted in the 1960s and early 1970s demonstrated the daytime superiority of fluorescent colors. Siegel and Federman (*9*) conducted laboratory and field studies on the detection and color recognition of fluorescent orange paints relative to ordinary colors. The first traffic study was a field study run by Hanson and Dickson (*10*) in which they compared a number of fluorescent and ordinary colors under typical daylight driving conditions. Asper (*11*) looked at the conspicuity of fluorescent slow-moving vehicle emblems. All of these studies concluded that fluorescent colors are significantly more visible (as determined by larger detection and recognition distances) than ordinary colors. Fluorescent colors consistently outperformed the ordinary colors over the entire range of daylight driving conditions—sunny,

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overcast, dawn, and dusk. In part on the basis of these studies, fluorescent colors are specified in a number of transportation and workplace safety signing applications (*12–14*).

Fluorescent orange is the best documented of the fluorescent colors. Its high conspicuity and exceptional warning value are unquestioned. The *Manual on Uniform Traffic Control Devices* (MUTCD) equates the "high conspicuity" of fluorescent orange directly to "an additional margin of safety" for the motorist (*1*). Fluorescent retroreflective sheetings have been known for 20 years (*15*), but they have not yet achieved widespread acceptance in outdoor signing applications. The primary reason has been the historically poor color stability of fluorescent signing materials. The complex photochemistry of fluorescence accelerates the degrading effects of solar radiation. As a result, the outdoor color durability of fluorescent sheetings has typically been an order of magnitude lower than ordinary signing colors. According to the International Commission on Illumination (CIE), changes in the color (hue) and luminance (brightness) of conventional fluorescent materials "may be readily apparent in even a few days" (*16*).

For signing applications in which the requirement for high visibility has outweighed color durability concerns, exceptionally large color limits are specified to allow for fluorescent color degradation over time. The region of CIE color space defining unrestricted fluorescent orange (*14*), a safety color for long-term outdoor use, is at least twice the size of the region allotted for orange retroreflective sheeting (ASTM D 4956-90). This type of approach attempts to balance the visibility benefits of fluorescent colors against the economics of sign replacement. Allowing even for considerable changes in color and loss of fluorescent emission intensity, fluorescent colors, and fluorescent orange in particular, typically last no more than 2 years outdoors. Specifying very large in-use color limits to compensate for marginal color durability may be practical for some color-coded systems, but it is not practical for roadway signing.

Until now only ordinary colorants systems have possessed the color durability required for retroreflective sheetings used in the CWZ. Recent technical developments are now leading to a redefinition of the contribution fluorescent colors can make toward improving the visibility of traffic control devices. A highly retroreflective fluorescent orange sheeting has been developed having color durability similar to ordinary traffic signing materials. The field study reported here was run to compare the visibility performance of the durable fluorescent orange retroreflective sheeting with both conventional fluorescent films and the ordinary orange retroreflective materials commonly used for CWZ signing. Visibility measurements were made at night using illumination from low-beam automobile headlights and under a range of typical daylight driving conditions. New and weathered samples of the fluorescent orange retroreflective sheeting were included in this study to evaluate the effect of long-term outdoor exposure on visibility performance.

FIELD STUDY: METHODOLOGY

Subjects

The study used a group of 14 adult licensed drivers (10 males and 4 females). All subjects were within normal limits for visual acuity and color vision when tested on a Bausch and Lomb Orthorater.

Site

The study was conducted during spring and late summer 1991 at the 3M Transportation Safety Center in Cottage Grove, Minnesota. This facility is a full scale mock-up of a U.S. Interstate highway. The viewings were held on a flat straightaway running north by northwest.

Driving Conditions

The daytime viewings were conducted under a wide range of natural daylight conditions. The daylight conditions (defined below) covered the range of ambient light intensities and spectral distributions typically encountered while driving:

1. Sunny—midday (11 a.m. to 2 p.m.) under a sunny clear sky,
2. Overcast—midday (11 a.m. to 2 p.m.) under heavy cloud cover, and
3. Civil twilight—the 30-min period immediately after sunset (all observations in this study were made under a clear sky).

The nighttime segment of the study was run under the illumination of low-beam automobile headlights. Nighttime viewings began a minimum of 1.5 hr after sunset.

Backgrounds/Targets

A description of the materials used as targets is provided in Table 1. The daytime chromaticity coordinates, coefficients of retroreflection (R_A), and (where appropriate) maximum spectral radiance factors were determined for each sample and background in accordance with established practices (*17*; ASTM D 4956-90; ASTM E 991-90). Color was measured on a HunterLab Labscan 6000 spectrophotometer equipped with circumferential viewing using illuminant D_{65} and the 2-degree CIE standard observer. Table 2 gives the color and R_A data. Two backgrounds were used: white and olive drab (OD). These were chosen to represent the range of background brightness and color encountered in nature. White is representative of highly reflective environments such as concrete buildings and snow, whereas the dark green OD represents the natural foliage of trees, shrubs, grass, and fields.

Nine samples were used in the study—one red, one white, and seven orange. The three ordinary orange materials (Samples 1, 2, and 3) cover the range of retroreflective brightness available for CWZ signing materials. Two of the fluorescent materials (Samples 3A and 3B) were retroreflective sheetings, and the other two (Samples C and D) were nonretroreflective films. Figure 1 shows a plot of the seven orange samples relative to the color limits for yellow and orange retroreflective sheetings set out in ASTM D 4956. Samples 3A and 3B were identical in construction, as were Samples C and D. The differences within each pair are the result of outdoor weathering. Samples 3A and C are unexposed samples. Samples

TABLE 1 Sample Identification and Construction

Samples	Color	Fluorescent Yes / No	Retroreflective Yes / No	Type of Retroreflector	Sample Condition New / Weathered
3A	Orange	Yes	Yes	Microprismatic	New
3B	Orange	Yes	Yes	Microprismatic	Weathered
C	Orange	Yes	No		New
D	Yellow	Yes[1]	No		Weathered
3	Orange	No	Yes	Microprismatic	New
2	Orange	No	Yes	Encapsulated Lens	New
1	Orange	No	Yes	Enclosed Lens	New
E	Red	No	No		New
F	White	No	No		New

[1] Initially this sample was fluorescent orange.

TABLE 2 Color/Coefficient of Retroreflection

Sample	CIE 1931 Chromaticity Coordinates[1] Y	x	y	Maximum Spectral Radiance Factor %	nm	Coefficient of Retroreflection (R_A)[2] cd/lux/m^2
3A	34.4	0.611	0.377	112.1	610	443
3B	26.5	0.593	0.385	76.3	610	451
C	44.4	0.642	0.351	205.6	610	0
D	55.2	0.449	0.461			0
3	15.5	0.603	0.389			647
2	15.5	0.543	0.401			119
1	24.3	0.575	0.398			35
E	6.8	0.600	0.317			0
F	80.9	0.312	0.331			1
Background						
White	80.9	0.312	0.331			
OD	9.2	0.331	0.364			

[1] Illuminant D65, CIE 2° standard observer
[2] R_A measured at 0.2° observation angle, beta 1 = −4, and beta 2 = 0

3B and D had been weathered outdoors for 1 year in Arizona (inclined 45 degrees from horizontal, south facing) before this field study. This type of exposure is commonly used to assess the long-term outdoor durability of signing materials. Ketola (*18*) has shown that weathering 1 year at 45 degrees is roughly equal to 2 years of vertical exposure, which is more typical of highway signing. The combination of high solar irradiance levels and hot temperatures encountered in Arizona represents a worst-case environment for fluorescent color materials.

Figure 1 shows that the nonretroreflective fluorescent film underwent a substantial color change during exposure. Sample D started out a highly saturated fluorescent orange color identical to Sample C, but after weathering it had faded to a washed-out nonfluorescent yellow. The fluorescent orange retroreflective sheeting experienced only a modest color change during the same exposure. The color difference between the weathered fluorescent retroreflective sheeting (Sample 3B) and the unexposed sample (3A) is due primarily to a decrease in the fluorescent emission intensity as indicated by a lower maximum spectral radiance factor. There was no significant change in the coefficient of retroreflection of Sample 3B compared with Sample 3A. The radical color change that occurred in Sample D during outdoor exposure rendered it unfit for

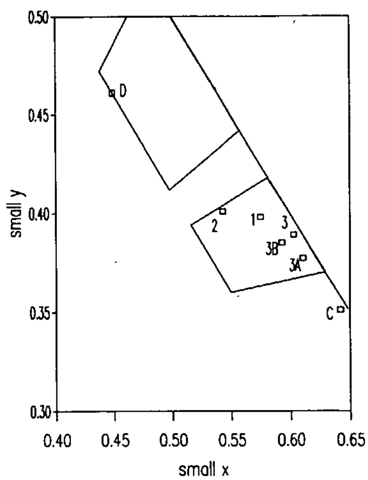

FIGURE 1 CIE 1931 chromaticity plot relative to ASTM D 4956 color limits for orange and yellow retroreflective sheetings.

CWZ signing applications in accordance with the MUTCD. For this reason Sample D was not included in the field study. All of the remaining samples used in the study were unweathered materials. The red and white targets were nonretroreflective films. Null points (white on white, OD on OD) were also run.

Protocol

The field study was conducted in a manner similar to that of Hanson and Dickson (*10*). Nine circular targets each 9.29 cm^2 (0.01 ft^2) in area were mounted in a random order onto background panels 1.22 by 1.22 m (4 by 4 ft) (Figure 2). These panels were mounted in the middle of the driving lane with the center of the panel 1.83 m (6 ft) off the ground. The subjects in automobiles drove toward the panel starting from a distance of 457 m (1,500 ft). Under daylight illumination no targets were detectible from this distance. As they approached the panel at dead slow (about 3.2 kph or 2 mph) the subjects recorded the following for each target position:

1. Detection distance—the distance at which the target can be differentiated from the background with certainty;
2. Recognition distance—the distance at which the target color (hue) can be identified; and
3. Color—the color (hue) the target was identified as possessing.

The subjects recorded their own data during each run using a data form consisting of a 3 by 3 grid with each cell corresponding to a specific target position. Subjects determined distances by referring to markings located every 3.05 m (10 ft) along the side of the road indicating the remaining distance to the background panel. Subjects were instructed to identify the target color (hue) with a single one-word name (white, green, red, etc.). Color names were not preassigned, leaving the subjects free to identify each target on the basis of their own color-naming criteria. Two practice runs were made before starting the experiment to train the subjects in how to fill out the data collection forms. Approximately equal numbers of approaches were made north- and southbound for the daylight conditions. At night where ambient illumination was independent of direction of travel, the approaches were made from only one direction for each background. The results of this study are based on 1,761 individual observations.

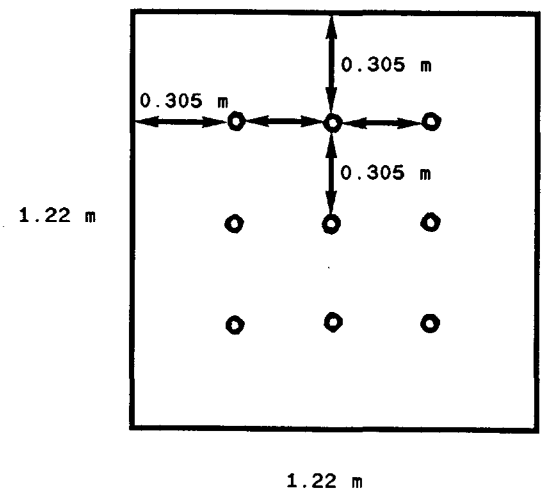

FIGURE 2 Background panel and target positions.

FIELD STUDY RESULTS

Detection and Recognition

The 85th percentile detection and recognition distance results are summarized in Table 3. Under a given set of conditions the 85th percentile distance represents the distance by which time at least 85 percent of the subjects had already detected/recognized the target. Traffic engineers commonly use the 85th percentile performance as the minimum design limits for traffic control devices. The values were interpolated from the probability-distance distributions for each condition and background. Analysis of variance (ANOVA) and two-way *T*-tests were run for each background and lighting condition. The results presented are all supported at the 95 percent confidence level by the statistical analysis.

Natural Illumination (Daytime)

Daytime Detection There were no substantial differences in the detection distances of any of the targets when viewed against the white background. Within each illumination condition the targets were all detected over the same range of distances, as shown in Figure 3. Against the dark OD background there was significant differentiation among the samples. The detection distances of the fluorescent materials were significantly larger than those of the ordinary orange samples. For example, Figure 4 compares the detection probability-distance curves for the two fluorescent orange retroreflective samples with the those of the two ordinary orange samples with comparable coefficients of retroreflection. The figure shows that under the poorest daytime visibility condition—civil twilight—the 85th percentile detection distances of the fluorescent retroreflective sheetings were 40 to 70 percent greater than the comparable ordinary orange sheetings. Under the best overall visibility condition—sunny—the two fluorescent orange sheetings still outperformed the ordinary materials by 20 to 40 percent. These results suggest that as the daytime lighting conditions deteriorate the fluorescent sheetings' visibility advantage increases relative to the ordinary signing materials.

Daytime Recognition Overall, the recognition distances of the fluorescent materials were much greater than those of the ordinary colors. The fluorescent retroreflective sheetings were recognized at significantly greater distances than the ordinary colors in almost every case. The new and weathered fluorescent orange retroreflective sheetings (Samples 3A and 3B) had equivalent recognition performance under nearly all daylight viewing conditions. One exception was the overcast/OD condition, where the 85th percentile recognition distance of the weathered sheeting was only 81 percent of the new sam-

TABLE 3 Eighty-Fifth Percentile Detection and Recognition Distances Versus Background

	Detection Distance (meters)[1]							
	Sunny		Overcast		Civil Twilight		Night	
Sample	White	OD	White	OD	White	OD	White	OD
3A	160	230	200	259	21	111	433	415
3B	223	262	209	230	37	93	442	437
C	195	344	187	270	43	116	27	37
3	191	187	216	178	43	64	442	442
2	209	154	216	166	43	66	277	276
1	212	241	215	183	43	98	154	142
E	245	105	200	87	55	14	30	11
F	--[2]	273	--	332	--	114	--	46
	Recognition Distance (meters)							
	Sunny		Overcast		Civil Twilight		Night	
Sample	White	OD	White	OD	White	OD	White	OD
3A	114	175	126	186	21	69	262	344
3B	94	186	96	151	18	64	244	218
C	134	201	133	206	24	84	15	2
3	93	143	34	99	15	23	285	218
2	27	117	43	91	3	23	180	168
1	72	139	66	122	6	43	91	72
E	14	52	27	73	3	8	3	0
F	--	78	--	44	--	38	--	0

[1] 1 m = 3.28 ft
[2] White on White null points.

ple's (Figure 5). Yet under those same conditions the weathered fluorescent sheeting was still recognized at distances up to 165 percent of the ordinary orange recognition distances.

Artificial Illumination (Nighttime—Low-Beam Headlights)

Nighttime Detection Not surprisingly, the nighttime detection distances using low-beam headlight illumination scaled directly with the coefficient of retroreflection and was independent of background color. Even the least bright retroreflective sheeting (Sample 1) was detected 3 to 4 times further away than the nonretroreflective films (Figure 6). No significant differences were found in the detection ranges of the three microprismatic sheetings (Samples 3, 3A, and 3B). This may be an artifact of the limited maximum viewing distance of 457 m (1,500 ft) used in the study.

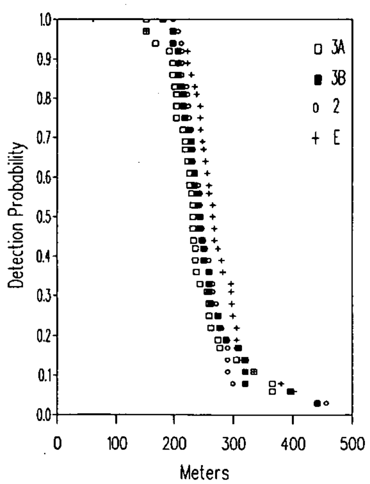

FIGURE 3 Daytime detection distance probability distribution of representative samples: overcast/ white background.

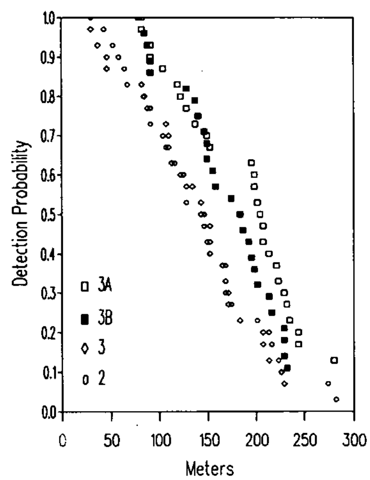

FIGURE 4 Daytime detection distance probability distribution of fluorescent and ordinary orange samples: civil twilight/OD background.

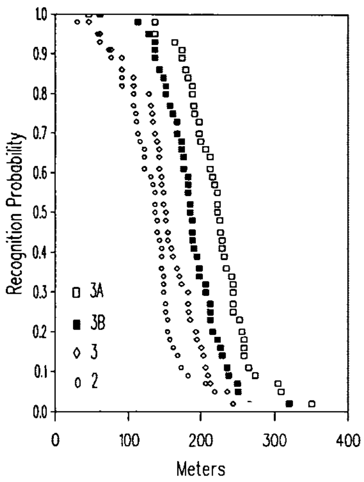

FIGURE 5 Daytime recognition distance probability distribution of fluorescent and ordinary orange samples: overcast/OD background.

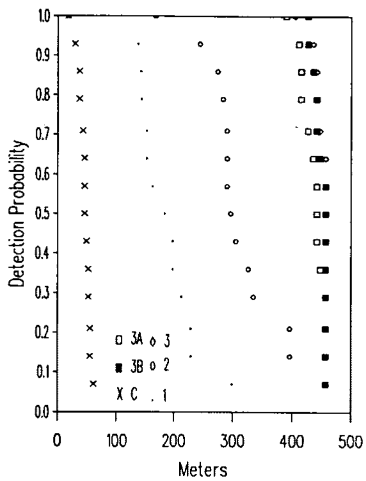

FIGURE 6 Nighttime detection distance probability distribution of samples: OD background.

Nighttime Recognition The nighttime recognition results mirror the detection results in most respects. The distances scaled with coefficient of retroreflection (Figure 7) and were generally independent of background color. Again, no significant differences were found between the three microprismatic sheetings. The recognition ranges for the microprismatic sheetings were significantly longer than for the enclosed lens or encapsulated lens sheetings. The nonretroreflective fluorescent orange and red films had extremely short recognition ranges. The subjects did not recognize the color of those films until they were practically on top of them.

Color Identification

The color identification results given in Table 4 are presented in terms of correct color recognition as a percentage of total presentations at each viewing condition. The correct color name for each sample was defined according to available industry specifications. The color of Sample C was defined in accordance with the ANSI Z535.1 color limits for unrestricted fluorescent orange (*14*). All the other samples were defined

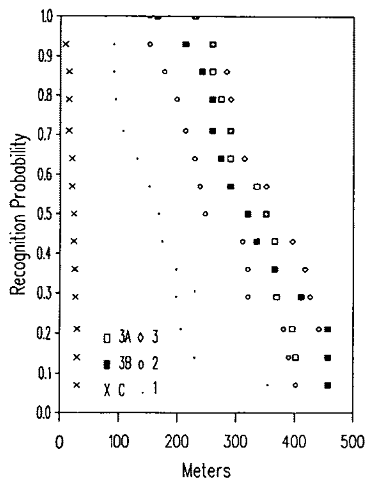

FIGURE 7 Nighttime recognition distance probability distribution of samples: white background.

TABLE 4 Color Identification Versus Background

		Correct Identification (%)							
		Sunny		Overcast		Civil Twilight		Night	
Sample	Correct Name	White	OD	White	OD	White	OD	White	OD
3A	Orange	100	95	86	95	95	100	93	93
3B	Orange	100	95	86	98	90	93	93	93
C	Orange	100	100	92	95	100	97	36	50
3	Orange	94	91	57	89	58	83	100	79
2	Orange	81	86	42	89	45	73	86	79
1	Orange	94	91	64	94	70	95	93	71
E	Red	88	95	64	100	50	97	14	57
F	White	--[1]	86	--	95	--	93	--	50

[1] White on White null points.

according to the daytime color limits set out in ASTM D 4956 for retroreflective sheeting used for traffic control devices. Under natural daylight the fluorescent orange samples were identified correctly a much higher percentage of the time and with greater consistency than the ordinary colors. The fluorescent retroreflective sheetings maintained their identifiability under poor visibility conditions, whereas the ordinary colors lost ground. Under nighttime driving conditions the retroreflective materials—fluorescent and ordinary—were typically identified correctly more than 80 percent of the time, whereas the nonretroreflective colors were correctly identified only 50 percent of the time.

DISCUSSION OF RESULTS

In 1963 the first field study to examine the visibility of fluorescent colors under typical driving conditions was conducted. That study compared the visibility of fluorescent and ordinary color nonretroreflective films under natural daylight. Retroreflective sheetings were known, but fluorescent retroreflective materials were not available. Now, almost 30 years later, this study has examined the effects of combining a fluorescent color and a high-efficiency retroreflector into a single signing material.

The ordinary orange retroreflectors each represent significant improvements in the nighttime visibility of traffic control devices. The all-weather performance of enclosed lens sheeting resulted in improved roadway safety when it was first introduced. Encapsulated lens sheeting constituted another major advance in nighttime visibility performance with a significant increase in the average nighttime visibility distance, but at the expense of some daytime conspicuity. The most recent advance in retroreflective performance is high-brightness microprismatic sheetings. At night these materials are visible at substantially greater distances than even the high-intensity encapsulated lens sheetings. In addition the microprismatic's highly saturated colors provide improved recognition day and night.

If this study only compared the performance of unweathered fluorescent sheeting with that of ordinary highway signing materials, the results would be interesting but would not have indicated the potential of durable fluorescent signing. Retroreflective fluorescent materials that are highly visible when brand new have been available for years. Limited color durability has made their use in conventional roadway signing applications impractical. When a bright fluorescent orange CWZ warning sign fades over the course of a few months to a dull yellow, it has lost almost all its warning value. Continually replacing these conventional fluorescent signs is uneconomical. However, not replacing the signs can lead to potentially dangerous situations since the reason for using fluorescent signing in the first place is to improve roadway safety by increasing the CWZ's visibility. The technology is now available to produce fluorescent colors durable enough for highway signing. After the equivalent of several years continuous outdoor exposure, the fluorescent orange retroreflective sheeting evaluated in this study still outperforms new samples of ordinary orange signing materials. Weathered fluorescent sheeting was included in this study to redefine the state of the art in retroreflective traffic control materials.

Fluorescent signing has finally developed to the point where it can substantially contribute to improving the overall visibility of traffic control devices. Because of developments in fluorescence technology it is now practical to optimize both the daytime and nighttime visibility of traffic control devices. This study reconfirms the role that retroreflective performance plays in determining nighttime visibility. It also demonstrates the daytime advantage of fluorescent signing, particularly under poor visibility driving conditions such as dawn, dusk, and adverse weather. The combination of durable fluorescent color with a highly retroreflective construction has produced a signing material with superior long-term visibility at all times, day and night, and in all types of weather.

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