

## DRIVER NEEDS, RETROREFLECTIVITY REQUIREMENTS, AND INFORMATION THROUGH WORD AND SYMBOL MARKINGS

The primary purpose of a roadway delineation system is to provide the visual information needed by the driver to safely maintain an intended travel path in a variety of situations. The delineation technique used must define the field of safe travel and it must be visible in daylight and darkness, as well as in periods of adverse weather such as rain and fog. Generally, the ability of a driver to operate a vehicle safely is based on the perception of a situation, level of alertness, the amount of information available, and the ability to assimilate the available information. The ideal form of delineation is that which provides the most guidance and warning to the driver. Research has been directed at defining the behavioral and perceptual characteristics of drivers and relating these human factors to the safety and operational efficiency of the nation's roadway system. Delineation information needed by drivers to safely drive at night is presented, including retroreflectivity and types of pavement markings that can provide additional information to drivers.

### INFORMATION NEEDED BY DRIVERS

Drivers encounter difficulties in nighttime guidance, particularly during periods of rain and fog, because the roadway delineation system does not function as well during adverse weather. For the typical driver, pavement markings often disappear at night, especially during adverse weather.

In addition to the stringent requirements for delineation created by the general populace, those with reduced or impaired vision, color vision deficiencies, or those driving under the influence of intoxicants have greater visibility needs. The most important group may be older drivers who need the improved visibility of roadway delineation features.

Figure 2 shows the difference in visual capability due to age (Adrian 1989). For a 65-year-old individual the threshold contrast value, which is the minimum difference between luminance of a target and the luminance of its background for detection, is seen to be an average of approximately twice the value for an individual of less than 23 years of age.

A driver's perception–reaction time continually increases with age because of decreased cognitive abilities and psychomotor skills (*Transportation in an Aging Society* . . .

1988). Increased perception–reaction time requires that the minimum required visibility distance for older drivers be increased with the complexity of decisional tasks. The use of brighter delineation to increase visibility distances and additional types and amounts of delineation to increase available information are required.

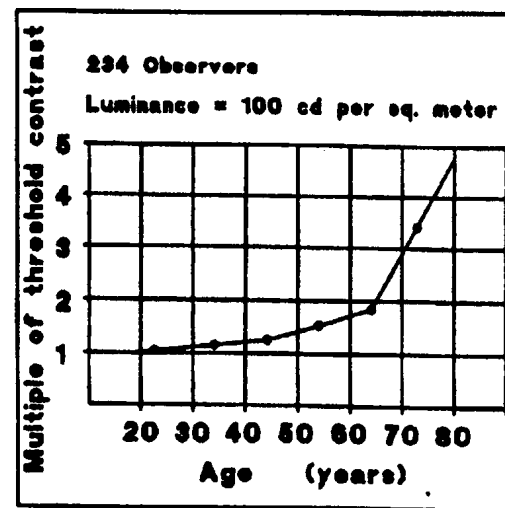


FIGURE 2 Threshold contrast requirement increases with age. (Source: Adrian 1989.)

Highway marking, signing, and other safety features provided for roads may not work adequately for all ages of drivers. In some cases, drivers 65 and older may require four times as much light to see as well as a 39-year-old driver. In addition, older drivers may look at fewer items in the roadway in a given time than do younger drivers. Therefore, it is important to provide older drivers with more redundant and brighter forms of delineation.

The nighttime visibility of a pavement marking is enhanced through retroreflection. Retroreflection is defined as the phenomenon that occurs when light rays strike a surface and are redirected directly back to the source of light (McGee and Mace 1987); that is, light from the vehicle's headlights strikes the marking and is redirected back toward the vehicle and driver's eyes, making the marking visible to the driver.

Pavement-marking retroreflectivity is represented by the coefficient of retroreflected luminance ( $R_L$ ), measured in units of millicandelas per square meter per lux

(mcd/m<sup>2</sup>/lux). Newly placed pavement markings often have  $R_L$  values of 250 mcd/m<sup>2</sup>/lux or more; however, with time and traffic passages, the retroreflectivity level deteriorates. The rate of deterioration of retroreflectivity depends on the type of marking material used and other factors such as type of pavement surface, traffic volume, and snow removal operations.

Retroreflectivity is typically provided by glass beads embedded into the marking material. The nighttime visibility of pavement markings is reduced when headlights are misaligned or dirty, or when windshields are dirty. The glare produced under these conditions becomes a significant problem for proper lane positioning, especially on highways with three or more lanes. Nighttime visibility is reduced further when markings are wet during rain and fog conditions. The visibility of the roadway is enhanced however by light from street lighting systems and other ambient light sources adjacent to the roadway, but not as a result of retroreflectivity.

Zwahlen and Schnell (1997) found that drivers operate with short preview times and do not appear to lower speeds under low-visibility conditions (temporary broken yellow centerline and no edge line) at night as compared with high-visibility conditions (restored double yellow centerline and white edge line). Zwahlen and Schnell determined that drivers travel too fast at night under low-visibility conditions and “overdrive” low-beam headlights. Increased retroreflectivity could provide relatively longer preview distances and preview times (Turner 1998).

Preview or visibility distance is the distance that the delineation provides the driver to see upcoming changes in roadway alignment (Migletz et al. 1994). It must provide sufficient time for the driver to detect the roadway features and alignment ahead and to respond with steering and speed adjustments. Preview distance is important because the view of the road ahead is limited, forcing drivers to rely on roadway and traffic information that is visible from only a short distance. The driver must respond quickly to perceived hazards or changes in alignment, making frequent steering and speed changes to correct for errors. Driver response requires heightened attention and concentration on brief glimpses of delineation from one moment to the next.

An FHWA study used computer simulations, observational field studies, and laboratory experiments to determine short- and long-range delineation requirements (Freedman et al. 1988). Delineation should provide a minimum of 2 s of preview time for short-range guidance in extreme situations; a value also established by Allen (1997). The 2-s preview time applies to extreme situations, including heavy rain or fog or glare from opposing headlights. At 40 km/h (25 mph), delineation must be visible at

least 23 m (74 ft) ahead. At 90 km/h (55 mph), delineation must be visible at least 49 m (162 ft) ahead. A pavement marking in new or good condition is typically adequate to provide these visibility distances.

Delineation should provide a minimum of 3 s of preview time for long-range guidance (Godthelp and Riemersma 1982; Freedman et al. 1988). Others accept it as a practical value, although 5 s was also recommended (*Visual Aspects* . . . 1988). When drivers are provided 3 s or more to view delineation, the task of guiding the vehicle is substantially easier. The driver is no longer constantly making rapid compensations for guidance errors and can rely more on roadway information farther ahead. Long-range information enables well-learned and more automatic driving skills that result in smoother steering and speed control. At 40 km/h (25 mph), delineation must be visible at least 34 m (110 ft) ahead. At 90 km/h (55 mph), delineation must be seen at least 74 m (243 ft) ahead. Raised retroreflective pavement markers (RRPMs) or other highly retroreflective materials are usually needed for this visibility distance.

A preview time of 3.65 s (3.00 s of reaction time and 0.65 s of eye fixation time) was selected by Zwahlen and Schnell as the performance measure in the calculation of minimum retroreflectivity values to accommodate the driver with a margin of safety and comfort. Minimum retroreflectivity values are speed dependent. A preview time of 2.00 s (1.35 s of surprise reaction time and 0.65 s of eye fixation time) was selected for determining the minimum required retroreflectivity of pavement markings on a fully marked road with RRPMs spaced at 24 m (80 ft) (Turner 1998).

The vehicle/observer geometry is representative of an average adult in an average large car. Old asphalt was selected as road surface because most roads in the United States are paved with old asphalt. Driver age was selected as 62 years or under, because 95% of the nighttime motorists in the United States are in this distribution. It is argued that RRPMs provide by far enough preview information to the nighttime driver and that the pavement markings are mainly needed for short-distance, quite often peripheral, visual information acquisition required for lateral placement control of the vehicle. Therefore, the minimum required retroreflectivity requirements for the pavement markings may be significantly reduced if RRPMs are used and properly maintained (Turner 1998). RRPMs that become dirty, damaged, or dislodged can be cleaned, repaired, and replaced. However, it is less practical to clean or repair an RRPM. RRPMs should be replaced on a regular schedule or left alone.

Table 2 lists the minimum levels of retroreflectivity recommended by Zwahlen and Schnell by speed class for

TABLE 2  
RECOMMENDED REQUIRED RETROREFLECTIVITY FOR  
PAVEMENT MARKINGS ACCORDING TO ZWAHLEN AND  
SCHNELL

Speed (mph)	Minimum Required $R_L$ (mcd/m <sup>2</sup> /lux)	
	Without RRPMS (preview = 3.65 s)	With RRPMS (preview = 2 s)
0–25	30	30
26–35	50	30
36–45	85	30
46–55	170	35
56–65	340	50
66–75	620	70

Notes: RRPMS = retroreflective raised pavement markers; 1 mi = 1.61 km.  
(Source: Turner 1998.)

roads with and without RRPMS. Many marking materials are capable of meeting these levels for roads without RRPMS when the markings are new, but cannot maintain them over the life of the material. It appears that older drivers cannot be accommodated at all speed levels. However, the addition of RRPMS makes it possible to accommodate most drivers (Turner 1998).

#### MINIMUM RETROREFLECTIVITY FOR NIGHTTIME VISIBILITY OF PAVEMENT MARKINGS

The FHWA is charged with developing a standard for pavement marking retroreflectivity (“Evaluation of Retroreflective Guidelines . . .” 1993). This section summarizes the findings of research to identify the minimum acceptable levels of retroreflectivity. Draft guidelines for minimum levels of retroreflectivity developed by the FHWA are presented. State and local agencies recommended minimum levels of retroreflectivity that are lower than those developed by the FHWA. The potential financial impact on transportation agencies implementing the guidelines is also presented. A comparison of dry and wet night retroreflectivity shows that markings could lose more than one-half of their retroreflectivity at night during wet pavement conditions.

#### Retroreflector Measurement Geometry

The standard for measuring pavement-marking retroreflectivity is the 30-m (98.4-ft) geometry. In other words, a typical driver views the marking at a location that is 30 m (98.4 ft) ahead of the vehicle. Figure 3 is a diagram of the 30-m (98.4-ft) geometry, which is also known as the European Committee for Standardization (CEN) geometry (*Road Marking Materials* . . . 1997; Hawkins et al. 2000). ASTM adopted the 30-m (98.4-ft) geometry as the U.S. standard (*Standard Test Method* . . . 1998). Table 3 shows the geometries and measurement angles of standard (Texas Transportation Institute 2001) and nonstandard instruments. The Mirolux 12, 12 m (39 ft) and Ecolux, 15 m (49 ft) instruments are now nonstandard instruments.

#### Minimum Threshold Value of Retroreflectivity for Pavement Marking Replacement

Research conducted by the Minnesota DOT (MnDOT) established a minimum threshold value of retroreflectivity (Loetterle et al. 1999). Study participants drove MnDOT automobiles during nighttime with headlights on low beam over a course comprised of two-lane state and county roads. They subjectively rated the visibility of the white edge lines and yellow centerlines. The average ratings for test sections were compared with retroreflectivity data collected with the MnDOT 30-m (98.4-ft) Laserlux retroreflectorimeter [with early 30-m (98.4-ft) geometry as shown in Table 3]. Results showed that the minimum acceptable level of retroreflectivity was between 80 and 120 mcd/m<sup>2</sup>/lux. MnDOT will use 120 mcd/m<sup>2</sup>/lux as the minimum threshold value of retroreflectivity.

#### FHWA Recommendations for Minimum Levels of Pavement-Marking Retroreflectivity

Section 406(a) of the 1993 Department of Transportation Appropriations Act requires the secretary of transportation to revise the MUTCD to include a standard for a minimum

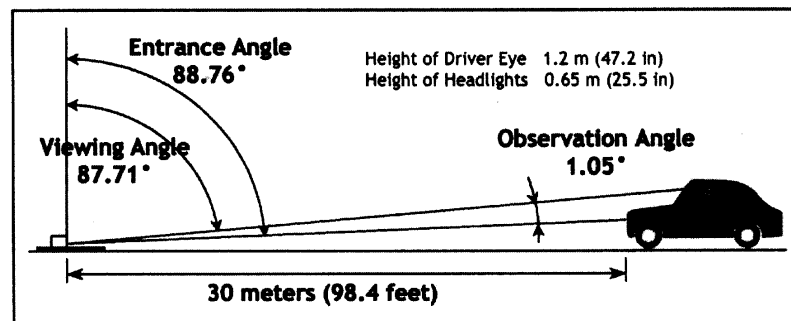


FIGURE 3 Standard 30-m measurement geometry for pavement marking retroreflectivity. 1 ft = 0.30 m. (Source: Hawkins et al. 2000.)

TABLE 3  
RETROREFLECTOMETER GEOMETRY

Measurement Geometry [m (ft)]	Entrance Angle (degrees) <sup>a</sup>	Observation Angle (degrees) <sup>b</sup>	Reflectometer
12 (39.4)	86.5	1.5	Mirolux 12 hand-held
15 (49.2)	86.5	1.0	Ecolux hand-held
30 (98.4) (early) <sup>c</sup>	88.5	1.0	Retrolux 1500 hand-held
			Laserlux mobile
30 (98.4)	88.76	1.05	Hand-held
			LTL 2000
			Mechatronic
			Mirolux Plus 30
			MX30
			Mobile
			ECODYN
			Laserlux

Note: 1 ft = 0.305 m.

<sup>a</sup>Entrance angle—angle between headlight beam and a plane normal to the pavement surface.

<sup>b</sup>Observation angle—angle between driver's sight line and the headlight beam.

<sup>c</sup>Originally built to what was believed was going to be the 30-m (98.4-ft) geometry.

{Source: [Texas Transportation Institute (HITEC Summary and discussions with experts) 2001].}

TABLE 4  
MINIMUM RETROREFLECTIVITY GUIDELINES FOR PAVEMENT-MARKING  
MATERIALS RECOMMENDED BY FHWA (mcd/m<sup>2</sup>/lux)

Material	Speed Classification <sup>a</sup>			
		Non-Freeway	Non-Freeway	Freeway
	Option 1	≤40 mph	≥45 mph	≥55 mph
	Option 2	≤40 mph	≥45 mph	≥60 mph
				>10,000 ADT
	Option 3	≤40 mph	45–55 mph	≥60 mph
White		85	100	150
White with/RRPMs <sup>b</sup>		30	35	70
Yellow		55	65	100
Yellow with/RRPMs <sup>b</sup>		30	35	70

<sup>a</sup>Retroreflectivity values are measured at 30-m (98.4-ft) geometry.

<sup>b</sup>Levels of retroreflectivity for the material classifications “White with RRPMs” and “Yellow with RRPMs” are for roads with supplemental delineation aids, retroreflective raised pavement markers (RRPMs), and/or roadway lighting.

(Source: Turner 1998.)

level of retroreflectivity to be maintained for pavement markings and signs (“Evaluation of Retroreflective Guidelines . . .” 1993). Retroreflectivity of signs and pavement markings is required for efficient traffic flow, driving comfort, and highway safety (“Field Evaluations . . .” 1993). Any text in the MUTCD is considered a standard and does not have to be a “shall” condition, but could be “should” (guidance) or “may” (option) conditions (Schertz et al. 2001).

The FHWA has developed candidate MUTCD criteria for retroreflectivity of pavement markings, but no such criteria have yet been approved and implemented as policy. Table 4 presents the FHWA-recommended minimum retroreflectivity guidelines and shows the options and factors included in the guidelines. Three options are included for discussion on the best way to include a good representation of roads and speeds. As speeds increase, drivers must be able to see much farther down the road to make safe path

adjustments and hazard avoidance maneuvers. The three roadway/speed classes proposed by the FHWA are based on the distribution of roadway types and speed limits in the United States.

Color of line is a factor in the guidelines. The retroreflectivity of yellow markings was found to be 35% less than the retroreflectivity of white markings (Migletz et al. 2000). Because white and yellow markings are usually replaced at the same time, the recommended minimum replacement value for yellow markings was reduced by 35% to reduce the financial burden on transportation agencies (Turner 1998).

The supplemental delineation aids RRPMs and roadway lighting are also factors in the guidelines. When present, they can provide the required visual cues necessary to allow drivers an appropriate preview time. Although pavement markings still provide close-in lateral placement and

TABLE 5  
MINIMUM RETROREFLECTIVITY GUIDELINES FOR PAVEMENT-MARKING MATERIALS  
RECOMMENDED BY STATE, COUNTY, AND CITY AGENCIES (mcd/m<sup>2</sup>/lux)

Material	Speed Classification <sup>a,b</sup>		
	Local and Minor Collector 48.3 km/h (30 mph)	Major Collector and Arterial 56.3–80.5 km/h (35–50 mph)	Highways, Freeways, and All Roads 88.5 km/h (55 mph)
White	Presence <sup>c</sup>	80	100
Yellow	Presence <sup>c</sup>	65	80

Note: 1 mph = 1.61 km/h.

<sup>a</sup>Retroreflectivity values are measured at 30-m (98.4-ft) geometry.

<sup>b</sup>Roads without retroreflective raised pavement markers (RRPMs) or roadway lighting.

<sup>c</sup>Presence is a pavement marking visible at night, but with no retroreflectivity value.

(Source: Hawkins et al. 2000.)

following information, supplemental delineation aids can provide drivers with improved distant visual information or a corresponding reduction in the required preview time. The minimum required level of retroreflectivity is reduced when supplemental delineation aids are present.

#### State, County, and City Agency Recommendations for Minimum Levels of Pavement-Marking Retroreflectivity

In the fall of 1999, the FHWA sponsored three workshops to discuss FHWA efforts to establish minimum levels of retroreflectivity for pavement markings (Hawkins et al. 2000). Input was obtained from representatives of 67 state, county, and city agencies. After reviewing FHWA guidelines, state and local agencies developed recommendations for pavement-marking retroreflectivity for roads without RRPMs or roadway lighting.

Workshop recommendations are presented in Table 5. When compared with the FHWA guidelines (presented previously in Table 4), the table shows that the three speed classifications were changed and retroreflectivity levels within each class were reduced. The most prominent change is in the “Local and Minor Collector” class with speeds ≤48.3 km/h (30 mph), where presence markings were recommended. A presence marking is a pavement marking visible at night, but with no retroreflectivity value (Hawkins et al. 2000). Workshop participants stated that in local jurisdictions streets and roads in that class make up a significant proportion of all roads. It was concluded that illumination provided by vehicle headlights is adequate to meet the visibility needs of most drivers and that if the marking has adequate contrast with the pavement surface, retroreflectivity is not needed to provide visibility.

Two types of contrast are of interest, color contrast and luminance or retroreflective contrast. Color contrast is the degree of difference in the color, or between the lightest and darkest, of the pavement marking and adjacent pavement surface. Luminance contrast is the ratio of luminance

from the marking to luminance from its surroundings, measured from the driver’s position (Migletz et al. 1994). That is, the relative difference in retroreflectivity between a pavement marking and the adjacent pavement surface (Migletz et al. 2000).

During daytime, color contrast is important for driver guidance. During nighttime, both color and luminance contrast are important, especially where there are no RRPMs or roadway lighting. From the driver’s perspective, there is concern that during night and wet (wet road, rain, and/or fog) conditions, markings that are not retroreflective are not visible and that drivers travel at their own risk regardless of poor geometrics, narrow roads, etc.

Workshop participants also recommended that the following issues be addressed before minimum retroreflectivity levels are approved and implemented (Hawkins et al. 2000).

- The relationship between pavement-marking retroreflectivity and safety,
- The impact of RRPM condition and performance on the minimum values, and
- The ability to reduce the minimum values if other types of devices (such as roadway lighting or delineation) are present on a roadway.

#### Impact of Minimum Threshold Retroreflectivity Values

There is currently no general agreement on the minimum level of retroreflectivity for pavement markings that is essential for safe nighttime operation on the highway. In the absence of established criteria for the minimum retroreflectivity of pavement markings, the threshold retroreflectivity values presented in Table 6 were used in FHWA research to evaluate the impact on state agency pavement marking budgets, determine the retroreflective requirements under wet night conditions, and define the end of pavement-marking service life (Migletz et al. 2000 unpublished data).



TABLE 6  
THRESHOLD RETROREFLECTIVITY VALUES USED IN FHWA RESEARCH  
(mcd/m<sup>2</sup>/lux)

Material	Roadway Type/Speed Classification		
	Non-Freeway (≤40 mph)	Non-Freeway (≥45 mph)	Freeway (≥55 mph)
White	85	100	150
White with RRPMS or lighting	30	35	70
Yellow	55	65	100
Yellow with RRPMS or lighting	30	35	70

Notes: Retroreflectivity values are measured at 30-m (98.4-ft) geometry, 1 mi = 1.6 km.

(Source: Migletz et al. 2000 unpublished data.)

Table 6 is the same as Table 4, but only Option 1 was used for FHWA research. Option 1 was used because the “Freeway” ≥88.5 km/h (55 mph) classification includes all freeways, whereas the other options exclude freeways with 88.5 km/h (55 mph) speed limits. The impacts on budgets and wet night retroreflectivity are discussed here and service life is addressed in chapter 7.

#### Impact on Transportation Agency Budgets

Implementation of FHWA threshold values may require changes to transportation agency pavement marking policies. There is concern that pavement marking budgets would have to be increased to meet these guidelines. There is also concern about potential liability problems and the fatalities that could not be reduced should the guidelines not be met. The FHWA has sponsored research to determine the impact of these threshold values if implemented as minimum retroreflectivity guidelines (Migletz et al. 1999; Migletz et al. 2000; Migletz et al. 2000 unpublished data).

Case studies determined the number of markings requiring replacement in the fall and spring and the cost to state agencies to replace the markings. The evaluation was based on survey data and on pavement-marking retroreflectivity collected from 1994 through 1996 and was not specifically designed to include a representative sample of pavement markings throughout the United States. The “typical” state was assumed to have 19,300 centerline-km (12,000 centerline-mi) of state-maintained roadways. The annual budget for pavement markings was \$12.6 million, which includes replacing paint markings each spring and durable markings after 3 years. This estimated budget does not include special expenditures such as reinstallation of markings after resurfacing projects (often with durable markings) and placement of marking types other than longitudinal lines (e.g., stop bars, turn-lane markings, turn arrows, and word messages). The material distribution was determined through discussion with state agencies and consisted of 90% paint (evenly divided between conventional solvent and waterborne) and 10% durable markings (evenly divided between epoxy, thermoplastic, and tape).

The materials were distributed evenly over all roadway types and all types and colors of lines. The case study for the typical state was developed to be representative of geographical areas that experience moderate to severe winters.

The length of pavement markings to be replaced and the replacement costs were done for pavement markings without the presence of RRPMS or roadway lighting. Two types of replacement criterion were used, mean retroreflectivity below the threshold values in Table 6 and 50% of retroreflectivity values below the threshold values. The percentages of markings that would be replaced in the fall and spring are shown in Table 7.

TABLE 7  
MARKINGS TO BE REPLACED BASED ON REPLACEMENT CRITERION

Replacement Criterion	Fall Replacement (%)	Spring Replacement (%)
Mean $R_L$ below threshold	24.2	47.3
50% of $R_L$ values below threshold	25.8	47.3

Table 8 compares the estimated budget for pavement markings based on spring replacement only and the estimated budget for spring and fall replacements based on statistical replacement criteria. The results show that statistical replacement criteria could require an increased annual expenditure of \$2.4 to \$3.5 million, depending on the statistical criterion selected, for replacing pavement markings in the fall season. In addition, all paint markings, as well as a portion of the durable markings, would require replacement each spring. The extent of durable markings requiring replacement would depend on the specified threshold value.

The budget based on the use of statistical replacement criteria is higher than the budget based on current policy by 20 to 29%, depending on the criterion selected. The increase in the marking budget occurs because some markings that are now replaced annually would need to be replaced

TABLE 8  
ESTIMATED COMPARISON OF ANNUAL PAVEMENT MARKING BUDGETS FOR A TYPICAL STATE WITH AND WITHOUT  
STATISTICAL REPLACEMENT CRITERIA

Statistical Replacement Criterion	Annual Pavement Marking Budget Without Statistical Replacement Criteria (\$) <sup>a</sup>	Annual Pavement Marking Budget with Statistical Replacement Criteria			Increase in Pavement Making Budget (%)
		Spring Replacement (\$) <sup>b</sup>	Fall Replacement (\$) <sup>c</sup>	Total (\$)	
Mean $R_L$ below Table 6 threshold	12,619,600	12,802,300	2,383,200	15,185,500	20.3
50% of $R_L$ values below Table 6 threshold	12,619,600	12,793,700	3,529,900	16,323,500	29.4

<sup>a</sup>Assumes replacement of all paint markings and one-third of durable markings each spring.

<sup>b</sup>Assumes replacement of all paint markings each spring plus 47.3% and 47.3%, respectively, of the total statewide mileage of durable pavement markings under the two statistical replacement criterion.

<sup>c</sup>Assumes replacement of 24.2% and 25.8%, respectively, of the total statewide mileage of pavement markings each fall under the two statistical replacement criterion.

(Source: Migletz et al. 2000 unpublished data.)

twice each year. Although meeting the replacement criteria represents an increase in funding (by \$2.4 to \$3.5 million), it is less than the cost of two fatalities. According to the National Safety Council, willingness to pay, or comprehensive cost concept, the cost of a fatality from a motor vehicle crash is estimated at \$3,214,290 ("Estimating the Costs . . ." 2000).

#### Comparison of Dry Versus Wet Retroreflectivity Levels of Pavement Markings

The threshold values used to define the end of pavement-marking service life shown previously in Table 6 are the desired levels of retroreflectivity for drivers under nighttime, dry pavement conditions. The FHWA has sponsored research to investigate the effect of rainfall on pavement-marking retroreflectivity (Migletz et al. 2000 unpublished data).

Retroreflectometers are capable of measuring the retroreflectivity of wet pavement markings (Texas Transportation Institute 2001). Mobile retroreflectometers, such as the Ecodyn and Laserlux, cannot be used effectively during rainfall, because such devices are not intended for making readings in the presence of the splash and spray generated by vehicles operating during a rainstorm. Splash and spray covers the lens of the retroreflectometer and reduces the amount of light received. Furthermore, even if measurement during a rainstorm were possible, it would be impractical in a large-scale survey to measure every site during rainy conditions.

To investigate the effect of rainfall on pavement-marking retroreflectivity, a technique was developed to simulate wet pavement conditions (Migletz et al. 2000 unpublished data). The retroreflectivity for 1.22-m (4-ft) sections of in-service white edge lines was measured under dry conditions. The edge line was then wetted by application of five back-and-forth passes of a paint roller saturated

with water. The water was allowed to run off the marking for 1 min and the retroreflectivity was then measured.

Since the FHWA research (Migletz et al. 2000 unpublished data), CEN Standard EN 1436:1997, which addresses collecting retroreflectivity measurements, wetting the marking prior to collecting measurements, and determining the intensity of rainfall, either simulated or actual rainfall was published (*Road Marking Materials* . . . 1997). In addition, ASTM has developed two methods for testing pavement-marking retroreflectivity under wet conditions, by spraying the marking with water (*Measuring the Coefficient* . . . 2001) and by pouring a bucket of water on the marking (*Test Method for Measuring* . . . 2001). The retroreflectivity of pavement markings for the FHWA experiment with dry and simulated wet pavement was measured with the Laserlux retroreflectometer parked on the roadway shoulder. Over a 3-year period, 424 sets of comparative dry and wet pavement measurements were made at 60 test sites that included a broad range of roadway, pavement, and material types; bead sizes; and bead distributions. These data were used to estimate the nighttime visibility of a marking under wet pavement conditions in comparison to comparable dry pavement conditions.

The results of the evaluation of pavement-marking retroreflectivity under simulated wet pavement conditions are presented in Table 9. This table shows that the pavement-marking retroreflectivity measured under wet pavement conditions was generally much lower than under dry pavement conditions. For edge lines whose retroreflectivity under dry conditions was greater than 300 mcd/m<sup>2</sup>/lux, the mean retroreflectivity for these sites was 423 mcd/m<sup>2</sup>/lux under dry pavement conditions and 179 mcd/m<sup>2</sup>/lux under wet conditions. Thus, the pavement-marking retroreflectivity under wet pavement conditions averaged only 42% of the comparable value under dry pavement conditions. Furthermore, the table shows that even for pavement markings with relatively good dry pavement retroreflectivity (between 200 and 300 mcd/m<sup>2</sup>/lux) that is clearly acceptable

TABLE 9  
AVERAGE DRY OVER WET PAVEMENT-MARKING RETROREFLECTIVITY RATIO

Retroreflectivity Range (mcd/m <sup>2</sup> /lux) Under Dry Conditions	Mean Retroreflectivity (mcd/m <sup>2</sup> /lux) Under:		
	Dry Conditions	Wet Conditions	Ratio Dry/Wet
≥300	423	179	2.24
200–300	244	108	2.29
150–200	174	88	1.93
120–150	133	64	2.28
100–120	109	48	2.07
80–100	89	46	1.97
60–80	71	31	2.25
<60	45	20	2.36
	Average ratio:		2.17

Note: Retroreflectivity was measured at early 30-m (98.4-ft) geometry (see Table 3).

(Source: Migletz et al. 2000 unpublished data.)

TABLE 10  
ESTIMATED MINIMUM WET RETROREFLECTIVITY VALUES BASED ON  
THRESHOLD VALUES USED TO DEFINE SERVICE LIFE FOR DRY  
CONDITIONS (mcd/m<sup>2</sup>/lux)

Pavement Marking Color and Environment	Roadway Type/Speed Classification		
	Non-Freeway (≤40 mph)	Non-Freeway (≥45 mph)	Freeway (≥55 mph)
White	185 (85)	217 (100)	326 (150)
White with RRPMS or lighting	65 (30)	76 (35)	152 (70)
Yellow	120 (55)	141 (65)	217 (100)
Yellow with RRPMS or lighting	65 (30)	76 (35)	152 (70)

Notes: The values in parentheses are the threshold values for dry pavement conditions shown in Table 6. The values not in parentheses are the retroreflectivity levels under dry pavement conditions that would be needed to achieve the Table 6 values under wet pavement conditions. Retroreflectivity values are measured at 30-m (98.4-ft) geometry (see Table 3). 1 mi = 1.6 km.

(Source: Migletz et al. 2000 unpublished data.)

under any likely threshold value for pavement-marking replacement, the retroreflectivity under comparable wet pavement conditions is 108 mcd/m<sup>2</sup>/lux, which is near or below many of the threshold values cited in Table 6.

Over the entire range of dry pavement retroreflectivity values shown in Table 9, the mean retroreflectivity under wet pavement conditions is between 42 and 52% of the retroreflectivity under dry pavement conditions. The last column in Table 9 shows the ratio of pavement marking retroreflectivity under dry and wet conditions. This ratio is relatively constant, ranging from 1.93 to 2.36, and averaging 2.17. This suggests that there may be a fairly consistent relationship between pavement-marking retroreflectivity under dry and wet conditions, with dry pavement retroreflectivity values being approximately 2.17 times greater than comparable wet pavement values.

The implications of this finding for setting threshold values for pavement-marking retroreflectivity are shown in Table 10. The retroreflectivity values shown in parentheses in the table are the threshold values for dry pavement conditions taken from Table 6. The values not in parentheses are retroreflectivity values under dry pavement conditions that would be needed to achieve the Table 6 threshold

values under wet pavement conditions. For example, the table shows that to achieve a wet pavement retroreflectivity of 150 mcd/m<sup>2</sup>/lux for a white marking on a freeway the marking would need to have a dry pavement retroreflectivity of 326 mcd/m<sup>2</sup>/lux. There are few pavement marking materials that can provide such high retroreflectivity levels, both initially and over time, that are indicated for sites without RRPMS and/or lighting, because the visibility of many pavement markings that would normally be considered good under dry pavement conditions is likely to be very low under wet pavement conditions. Under nighttime wet pavement conditions a pavement marking often loses enough retroreflectivity that it becomes unacceptable. RRPMS in good condition maintain retroreflectivity under nighttime wet pavement conditions and are good supplements to pavement markings.

#### INFORMATION THROUGH PAVEMENT WORD AND SYMBOL MARKINGS

Pavement word and symbol markings are used to provide additional driver information. Practices in the United States, Canada, and Europe are described in this section.



### United States and Canadian Word and Symbol Markings

Word and symbol markings, addressed in Section 3B.19 of the MUTCD, are used to regulate (e.g., STOP), warn (e.g., STOP AHEAD), or guide (e.g., US-40) traffic [MUTCD 2000 (2000)]. Except as otherwise noted in the MUTCD, markings shall be white. Standard plans developed by state agencies provide examples of word and symbol markings as shown in Figures 4 and 5.

Symbol messages are preferable to word messages. Letters and numbers should be 1.8 m (6 ft) or more in height. Agencies such as the Texas and California DOTs use an increased standard height of 2.4 m (8 ft) ("Standard Plans" 1998B; "Pavement Markings, Symbols and Numerals" 1999). The spacing between lines of pavement markings is based on the speed of the road. For example, on roads with speed limits less than or equal to 72 km/h (45 mph), the minimum spacing is four times the letter height. On roads with speed limits greater than 72 km/h (45 mph), the minimum spacing is four times the letter height and the maximum spacing is 10 times the letter height ("Standard Plans" 1998A). The California DOT (Caltrans) permits the spacing to be reduced appropriately where there is limited space because of local conditions ("Pavement Markings, Words" 1999). Redundant and dual messages are used to reinforce information provided to drivers.

Examples of redundancy in U.S. practice include the "STOP" message, which is accompanied by a stop line and STOP sign. The yield-ahead triangle symbol or "YIELD AHEAD" marking is not used unless a "YIELD" sign is in place. Where through lanes approaching an intersection become mandatory turn lanes, lane-use arrow markings are used and accompanied by standard signs. The "ONLY" marking may be used to supplement lane-use arrow markings.

Out of 51 survey responses, only the Colorado DOT provided an example of a word and symbol marking other than those in Part 3 and that is "DO NOT BLOCK INTERSECTION."

### European Word and Symbol Markings

The FHWA sponsored an international technology scanning program to Europe to observe innovative traffic-control practices, including pavement markings, and identify those that could be implemented in the United States (Tignor et al. 1999). The European practice provides road users with a greater amount of information than is provided by pavement markings in the United States. The pavement marking message is directly in the driver's line-of-sight, a safety benefit, especially for older drivers in any traffic and all drivers in moderate-to-heavy traffic. The prevalent use



FIGURE 4 Word pavement marking details. (Source: Texas DOT 1998.)

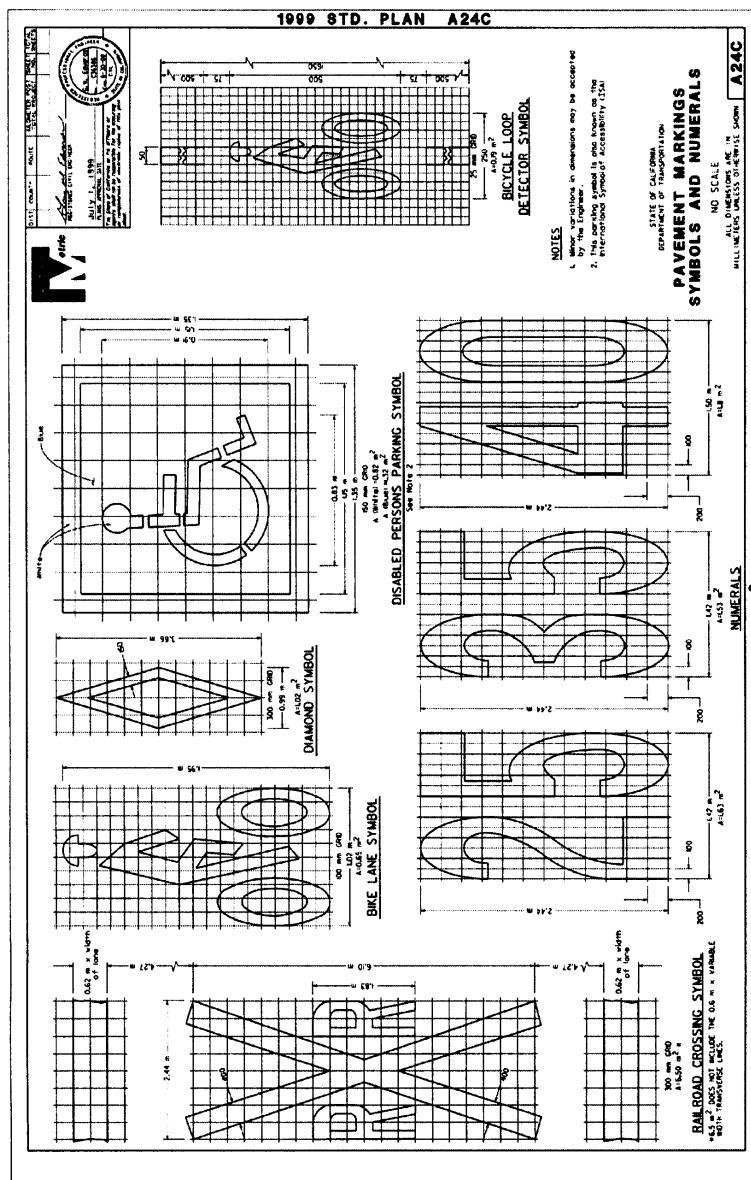


FIGURE 5 Pavement markings symbols and numerals. (Source: Caltrans 1999.)



is referred to as “horizontal signing.” The redundant applications improve efficiency and safety for road users. England uses this concept quite liberally in addition to providing redundant or dual messages in many warning and regulatory sign applications.

Examples of European horizontal signing are listed here and shown in Figures 6 through 11. These markings are also addressed in the MUTCD.

- Highway numbers, with arrows where necessary, at intersections and on off-ramps leading to the highway, where two or more highways converge/diverge;
- “Stop” and “Yield” markings on the approaches to intersections, roundabouts, and pedestrian crossings;
- Markings indicating traffic or parking prohibitions;
- Bus lane markings;
- School markings;
- Lane markings carried through intersections; and
- Dotted edge lines through exit and entrance ramps at interchanges that are often wider than the normal edge line.



FIGURE 6 Highway numbers in lanes, England. (Source: Tignor et al. 1999.)

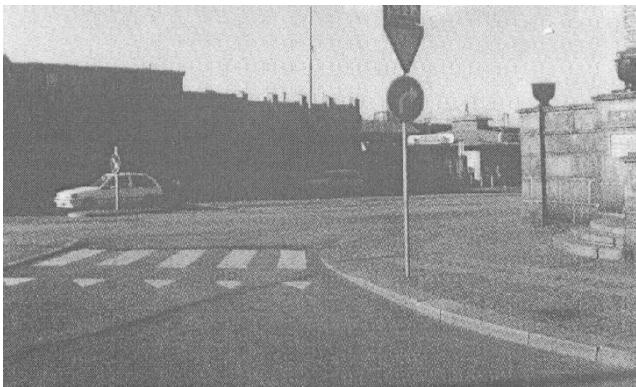


FIGURE 7 Yield pavement markings, Sweden. (Source: Tignor et al. 1999.)

#### *All-White Pavement Markings*

All-white pavement markings may have implementation value in the United States. The NCHRP is researching the



FIGURE 8 Intersection marking, England. (Source: Tignor et al. 1999.)



FIGURE 9 Bus lane marking, Sweden. (Source: Tignor et al. 1999.)



FIGURE 10 Abbreviated markings carried through intersection, Germany. (Source: Tignor et al. 1999.)

feasibility of an all-white marking system under Project 4-28. However, it is believed that significant effort would be associated with the implementation of an all-white system of pavement markings in the United States. Standards





FIGURE 11 Markings on rural freeway on-ramp, France. (Note: edge line marking carried across ramp.) (Source: Tignor et al. 1999.)

would have to be changed, new markings placed, and drivers educated. Implementation would likely require that agencies devote greater resources to markings than they currently do. The potential benefits of an all-white system over a yellow–white system include greater visibility, better contrast, lower cost, improved application efficiency, reduced storage demands, reduced hardware requirements, and increased consistency with international practices. A disadvantage of an all-white system is the educational effort that would be required prior to and during implementation (Hawkins 2000). The change may also require coordination with other countries that use a yellow–white system (Canada and Australia).

Since the publication of the 1971 MUTCD, yellow has been used exclusively for separating opposing traffic (centerline application) (Hawkins 2000). Before 1961, a centerline could be white or yellow, depending on the type of line. A double solid line and the no-passing barrier line were yellow. A single broken line was white.

### *Tiger Tail*

Tiger tail freeway entrance/exit ramp markings may have implementation value in the United States. The tiger tail or anti-swooping pavement marking pattern for freeway entrance and exit ramps is used in England. Figure 12 shows that the marking separates two-lane entrance or exit ramp traffic with a wide painted buffer that separates the merge location and the turbulence because of the two entering maneuvers. The treatment requires a wider and longer entrance or exit ramp than a side-by-side, two-lane ramp, but capacity is increased and conflicts are reduced. Tiger tail markings have also been implemented on freeway exit ramps in England as shown in Figure 13. They result in smoother traffic flow, less driver stress, and increased exit capacity, because of a decrease in erratic maneuvers at gores.

An implementation obstacle is that multilane ramps require greater pavement area than is normally found on U.S. freeways. Revision of geometric design standards for multilane entrance and exit ramps would be required. The

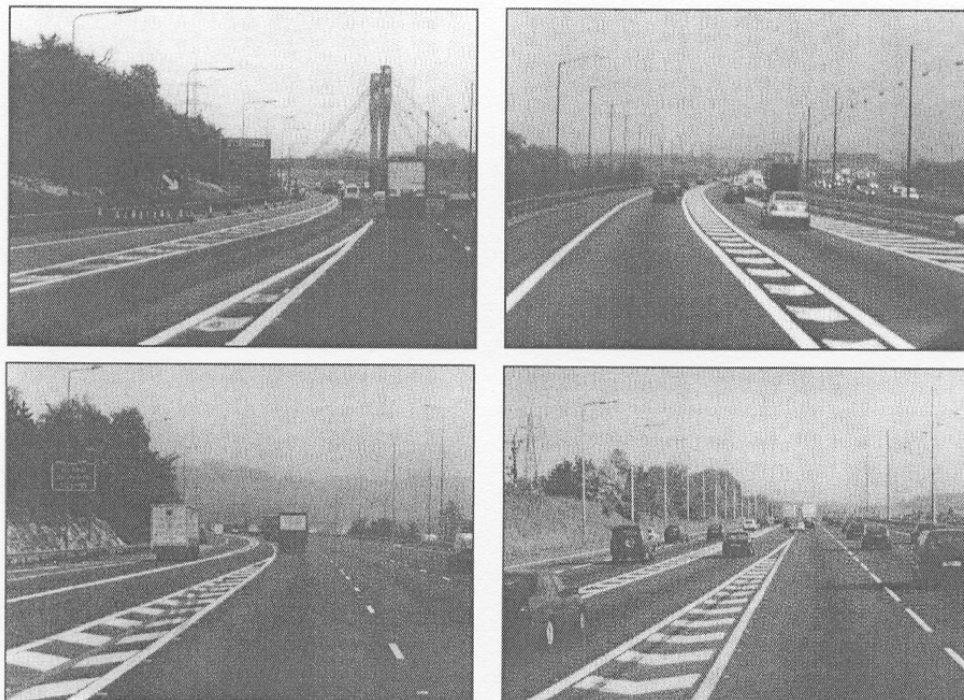


FIGURE 12 Tiger tail pavement markings on entrance ramps to English freeways. (Source: Tignor et al. 1999.)

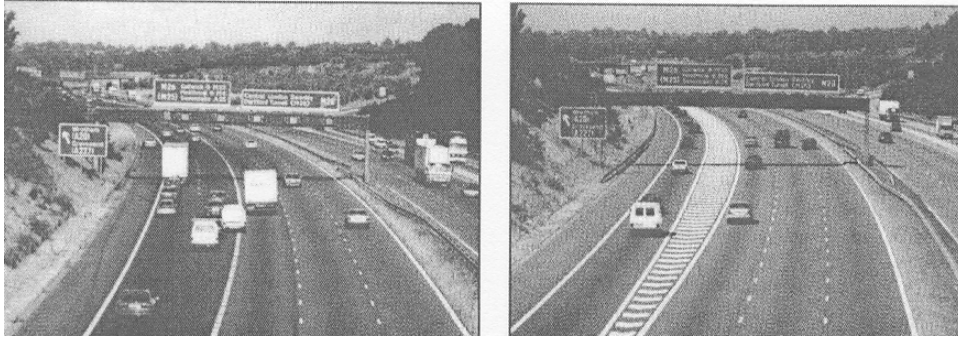


FIGURE 13 Before-and-after application of tiger tail marking on exit ramp. (Source: Tignor et al. 1999.)

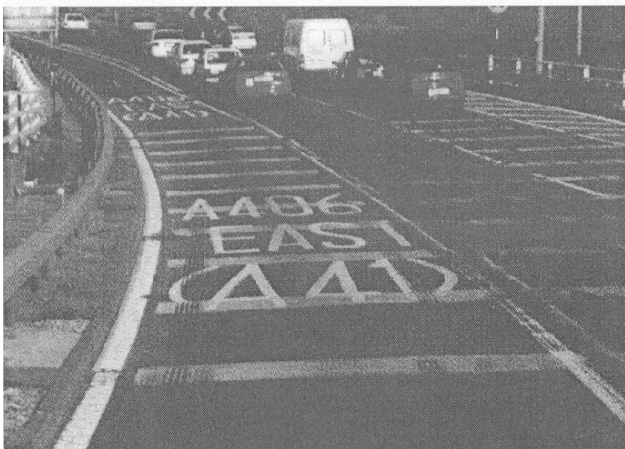


FIGURE 14 Use of parentheses (Route A41) in pavement markings, England. (Source: Tignor et al. 1999.)

tiger tail marking may be especially useful where two turning lanes feed the freeway entrance ramp from the crossroad. It equalizes the traffic in the two turning lanes, thus reducing the length of the left-turn signal phase.

#### *Use of Dotted Border for Trailblazing*

Dotted borders or parentheses are used with a route number to indicate a road that connects to the indicated route (a 'TO' or trailblazer message). The practice is usually applied at freeway exit lanes as shown in Figure 14. It de-emphasizes the number of the connector route to emphasize the route of greater importance. In England, parentheses are used to indicate the same 'TO' message and are used for pavement markings and signs.

#### *Chevrons for Vehicle Spacing*

In England, chevron markings are spaced at 40 m (131 ft) in traffic lanes to indicate the proper vehicle spacing. The sign shown in Figure 15 informs drivers to keep two chevrons

apart from the vehicle in front. The following benefits were achieved with chevron markings:

- A reduction of about 15% of drivers "close-following,"
- Fifty-six percent fewer injury accidents,
- Eighty-nine percent fewer single-vehicle accidents,
- \$1.2 million in accident savings (1993 prices),
- The effect can last at least 18 km (11.2 mi), and
- Benefits are 80 times the installation cost.



FIGURE 15 Chevron marking sign. (Source: Tignor et al. 1999.)

#### *Colored Pavements*

Pavement surface coloring in England and France indicates lanes for specific classes of vehicles as shown in Figures 16 and 17. In London, a red pavement surface is used to indicate a bus-only lane. In France, a light-green marking indicates where a bike lane intersects a traffic lane at a rotary intersection.





FIGURE 16 Red-colored bus lane, England. (Source: Tignor et al. 1999.)



FIGURE 17 Green pavement where bike lane intersects vehicle lane, France. (Source: Tignor et al. 1999.)

### *Pedestrian Treatments*

Throughout the four countries visited, there is a much higher degree of pedestrian traffic than is found in equivalent U.S. situations. Greater use of public transportation in Europe results in a greater amount of pedestrian traffic from the public transportation stop to the eventual destination. Several treatments address pedestrian–vehicle conflicts.

### *Raised Crosswalks*

A raised crosswalk is a flattop-style speed hump with a marked crosswalk on the plateau portion of the hump. In all four countries visited, raised crosswalks were observed at intersections in both residential areas and commercial districts. The raised crosswalk enhances the visibility of the crosswalk (and pedestrians who are crossing), reduces the speed of vehicles approaching the crosswalk, and increases the chances of an approaching driver stopping for a pedestrian in the crosswalk.

The safety of pedestrians, especially at mid-block crosswalks, was impressive. Although only approximately 8% of drivers stop for waiting pedestrians at a normal crossing, approximately 30% stop at raised crosswalks.

### *Advance Pedestrian Pavement Markings*

England uses zigzag markings to warn drivers of a pedestrian crossing, as shown in Figure 18. Placed on both sides of a lane, they provide more warning than crosswalk markings alone.

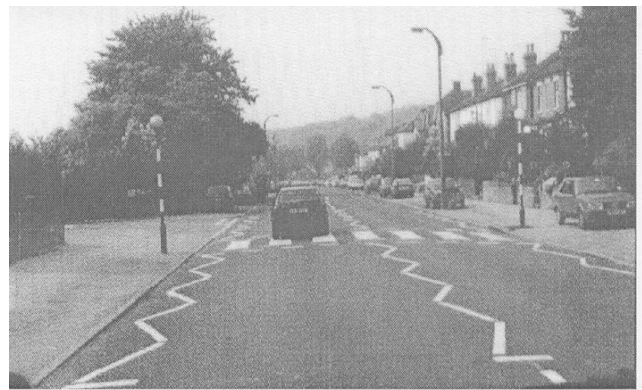


FIGURE 18 Markings on approach to pedestrian crossing, England. (Source: Tignor et al. 1999.)

## **SUMMARY**

Drivers encounter difficulties in nighttime guidance because pavement markings often disappear at night, especially during rain and fog. The visibility of pavement markings at night is dependent on their retroreflectivity, which represents the portion of incident light from a vehicle's headlights reflected back toward the driver's eyes. Increasing retroreflectivity can increase pavement marking preview or detection distances.

A preview time of 2 s was found to be the minimum acceptable limit on roads with pavement markings and RRPMS that are properly maintained. A preview time of 3 s is needed to provide long-range guidance information. Long-range information enables well-learned and more automatic driving skills that result in smoother steering and speed control.

Research recommended the minimum retroreflectivity levels for roads without RRPMS (3.65 s of preview time) and roads with RRPMS (2.00 s of preview time). New markings can meet the levels of retroreflectivity on roads without RRPMS, but cannot maintain them over the life of the material. Older drivers require more light to see delineation

and also are slower to react (increased perception–reaction time). It appears that older drivers cannot be accommodated at all speed levels with pavement markings. However, the addition of RRPMS makes it possible to accommodate most drivers.

The standard for measuring retroreflectivity is the 30-m (98.4-ft) geometry. MnDOT recommended 120 mcd/m<sup>2</sup>/lux as a minimum threshold value of retroreflectivity on dry pavement. The FHWA is currently developing MUTCD policy criteria for retroreflectivity based on speed, road class, color of line, and presence or absence of roadway lighting or RRPMS. The MnDOT recommendation meets FHWA policy criteria, except for white lines on freeways without lighting or RRPMS (150 mcd/m<sup>2</sup>/lux). The FHWA has sponsored workshops to obtain feedback on minimum threshold values. Some state and local agencies seek minimum threshold values lower than both the FHWA criteria and the MnDOT recommendation.

The FHWA has sponsored research to determine the impact of the minimum threshold values on a state agency. To meet the minimum values, a typical state agency may have to replace as much as 25% of the markings in the fall and 45% in the spring, while increasing the pavement marking budget by 20 to 29%. A reduction of less than two fatalities would offset the additional cost.

Pavement marking retroreflectivity under wet pavement conditions averaged only 46% of the comparable values under dry pavement conditions. For example, to achieve a wet pavement retroreflectivity of 150 mcd/m<sup>2</sup>/lux for a white marking on a freeway the marking would need a dry pavement retroreflectivity of 326 mcd/m<sup>2</sup>/lux. Markings

that would meet minimum retroreflectivity levels on dry pavements could be unacceptable on wet pavements.

A scanning tour of European pavement marking practices in 1998 revealed that many European countries communicate information by means of pavement markings to a much greater extent than in the United States and Canada. Europeans feel that the redundancy provided by a greater use of word and symbol markings, known as horizontal signing, is an important element in attaining and improving the efficiency and safety of road users.

The tour recommended that both all-white pavement markings and tiger tail ramp markings be studied for U.S. implementation. All-white markings offer several advantages, including a higher visibility level than yellow markings. However, educational efforts would be required for U.S. and Canadian drivers to understand the meaning of an all-white system of markings. In the United States, both white and yellow markings are used for centerlines. Since 1971, yellow has been used exclusively for separating opposing traffic (centerline application).

The tiger tail marking separates two-lane entrance and exit ramp traffic. It requires a wider and longer entrance or exit ramp than a side-by-side, two-lane ramp, but capacity is increased and conflicts are reduced.

Chevron markings spaced at 40 m (131 ft) are placed in traffic lanes to indicate proper vehicle spacing. They are supplemented with a sign informing drivers to keep two chevrons apart from the vehicle in front. The markings reduce tailgating and accidents and have an 80:1 benefit-cost ratio.